The Fourier-Kelvin Stellar Interferometer (FKSI) -- *A* ***Exploring Exoplanetary Systems with an Infrared Space Mission***

W. C. Danchi

Missions for Exoplanets: 2010-2020
Pasadena, CA

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Notes and Outline

- *Some of the talk is based on the Exoplanet Forum 2008 presentation for the committee on "Direct Detection of Exoplanets with Infrared Interferometry."*
- *The complete talk and draft report are available on the web.*
- *Contributions from many others include those who have been involved in the ExoPTF whitepaper, ACMCS proposal on FKSI, and Exoplanet Forum teams, and PPP RFI response.*
- *There are about 1 dozen papers written on various aspects of FKSI, and are available through the Astronomical Data Service or from the authors.*

- Brief Outline
  - Scientific Motivation
  - Mission Design Considerations
  - Performance
  - Technical Readiness
  - Conclusions

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1.1 Contributors

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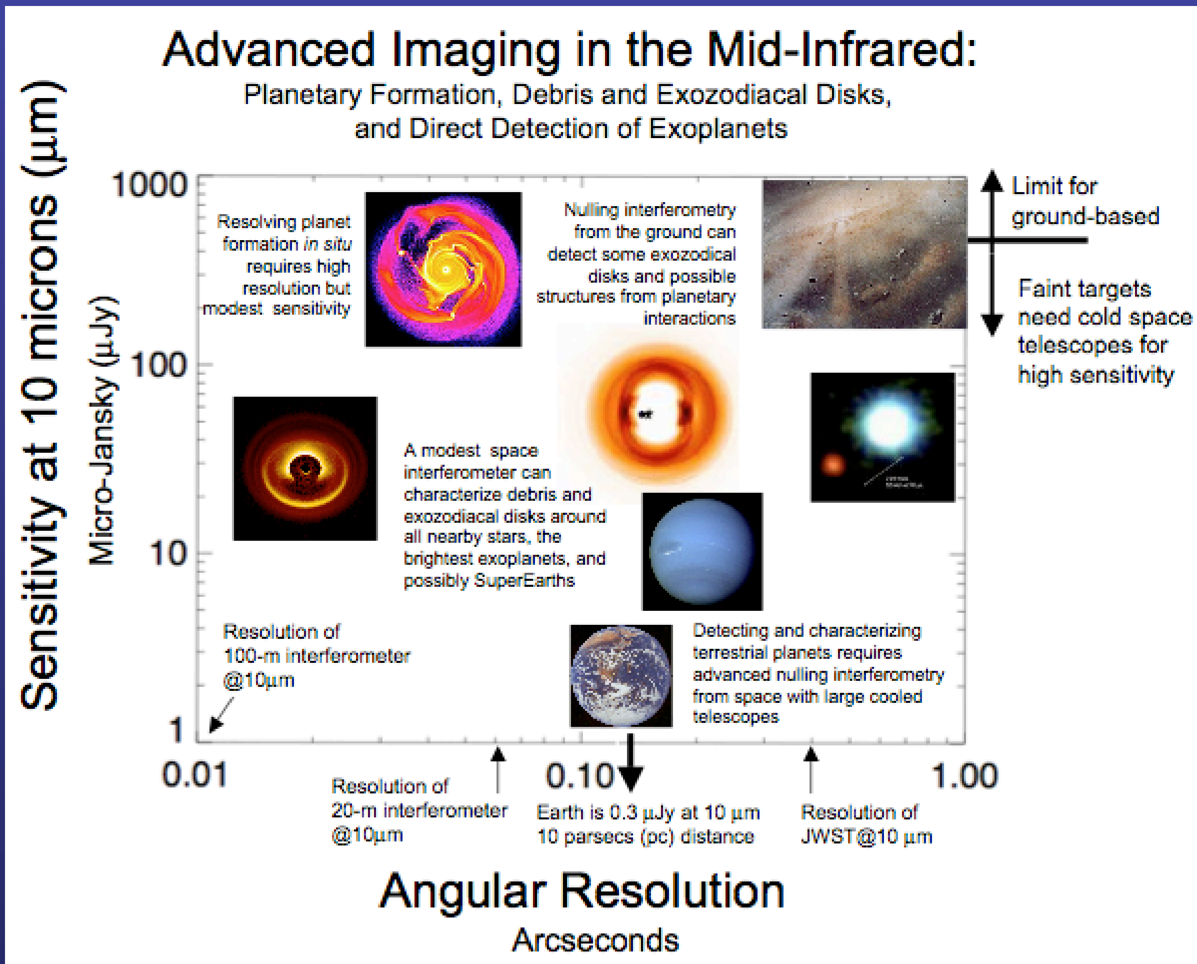
Sensitivity and Resolution in the Mid-IR



Ground-based interferometry in the IR:

- Limited sensitivity
- Long baselines available
- Good for studying protoplanetary disks

Space-based interferometry:

1. Structurally Connected interferometer (limited baseline length)

- Exozodi levels for ALL TPF/Darwin stars
- Debris Disks
- Characterize Warm & Hot Planets & Super Earths

2. Formation-flying or tethers (long baselines)

- Detect and characterize many Earth-sized planets
- Transformational astrophysics

Observations and some findings

•Advanced imaging with both high-angular resolution and high sensitivity in the mid-infrared is essential for future progress across all major fields of astronomy.

•Exoplanet studies particularly benefit from these capabilities.

•Thermal emission from the atmospheric and telescope(s) limits the sensitivity of ground-based observations, driving most science programs towards space platforms.

•Even very modest sized cooled apertures can have orders of magnitude more sensitivity in the thermal infrared than the largest ground-based telescopes currently in operation or planned.

•We find a mid-IR interferometer with a nulling (coronagraphic) capability on the ground and a connected-element space interferometer both enable transformative science while laying the engineering groundwork for a future "Terrestrial Planet Finder" space observatory requiring formation-flying elements.

Findings Concerning the Performance of a Small Structurally Connected Interferometer

•To date, progress has been made on the physical characteristics of planets largely through transiting systems, but a small planet finding interferometer can measure the emission spectra of a large number of the non-transiting ones, as well as more precise spectra of the transiting ones.

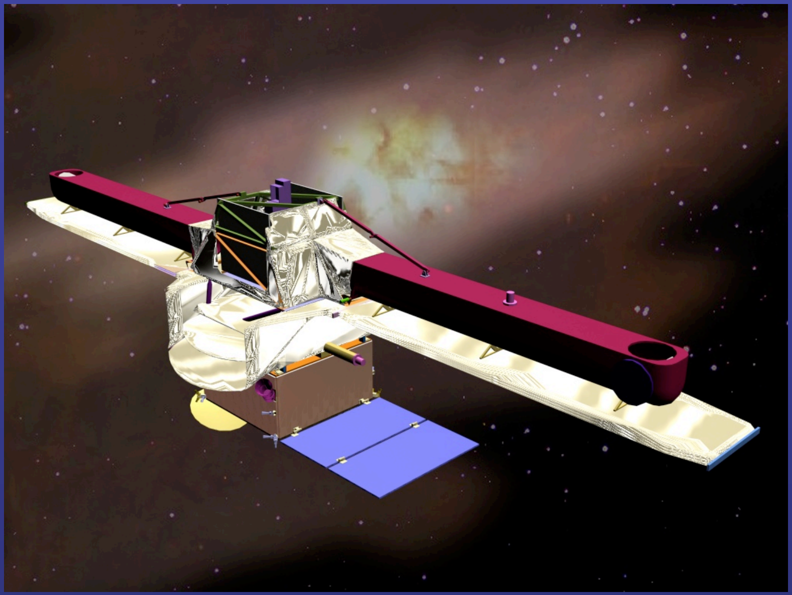
•As a conservative estimate, we expect that a small system could detect (e.g. remove the sin(i) ambiguity) and characterize about 75-100 known exoplanets.

•A small mission is ideal for the detection and characterization of exozodiacal and debris disks around ALL TPF candidate stars in the Solar neighborhood

•If the telescopes are somewhat larger than has been discussed in some of the existing mission concepts (e.g., 1-2 m) and are somewhat cooler (e.g., < 60K) so that the system can operate at longer wavelengths, it is possible for a small infrared structurally-connected interferometer to detect and characterize super-earths and even ~50-75 earth-sized planets around the nearest stars.

•Further studies of the capabilities of a small infrared structurally-connected interferometer are necessary to improve upon our estimates of system performance

A Small Structurally Connected Interferometer: The Fourier-Kelvin Stellar Interferometer (FKSI) Mission



PI: Dr. William C. Danchi
Exoplanets & Stellar Astrophysics, Code 667
NASA Goddard Space Flight Center

Technologies:

- •Infrared space interferometry
- •Large cryogenic infrared optics
- •Passive cooling of large optics
- •Mid-infrared detectors
- •Precision cryo-mechanisms and metrology
- •Precision pointing and control
- •Active and passive vibration isolation and mitigation

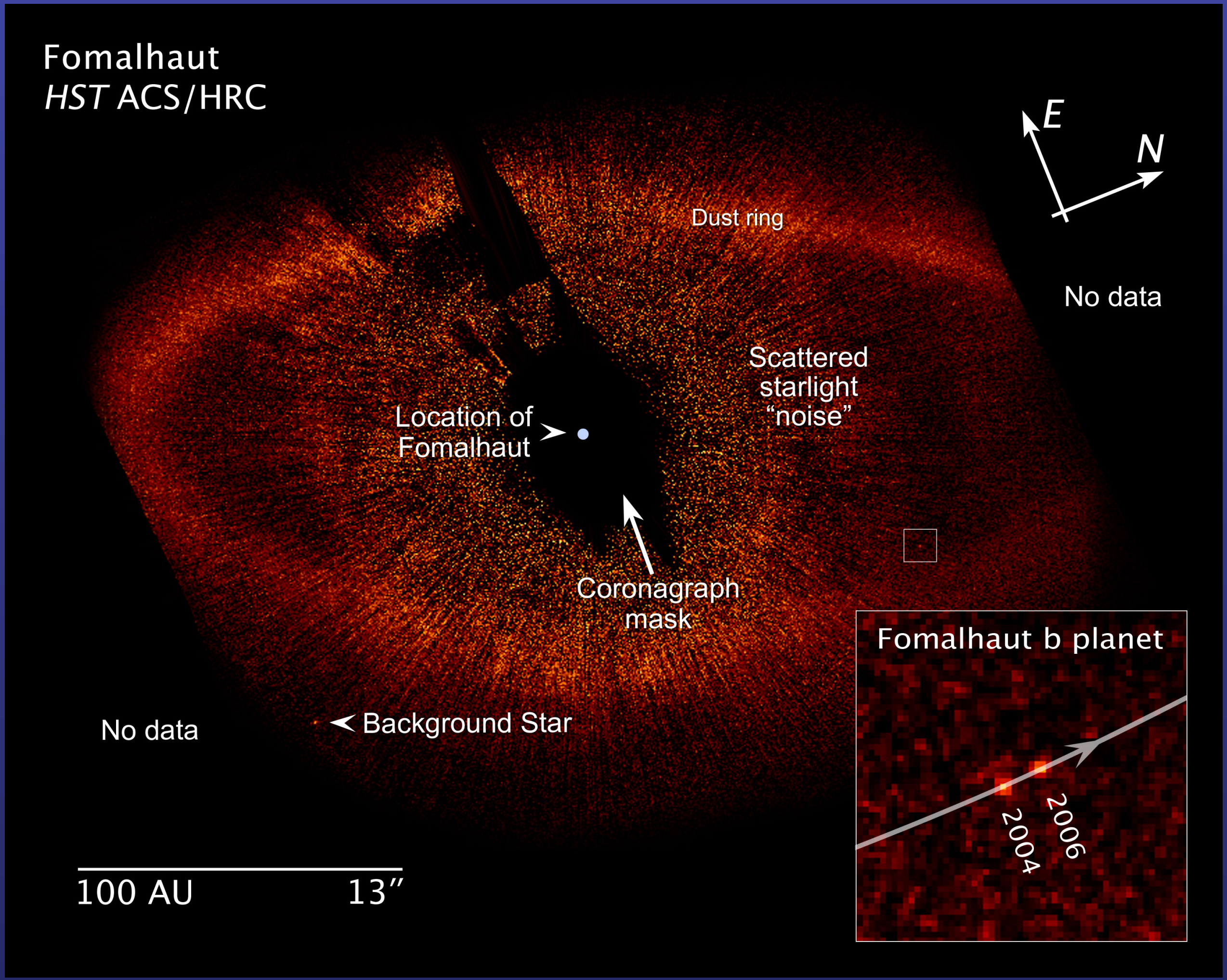
Key Features of Design:

- •~0.5 m diameter aperture telescopes
- • Passively cooled (<70K)
- • 12.5 m baseline
- • 3 – 8 (or 10 TBR) micron science band
- • 0.6-2 micron band for precision fringe and angle tracking
- • Null depth better than 10^-4 (floor), 10^-5 (goal)
- • R=20 spectroscopy on nulled and bright outputs of science beam combiner

Key Science Goals:

- **Detect and Characterize Super-Earths around nearby stars**
- **Observe Circumstellar Material**
  - Exozodi measurements of nearby stars and search for companions
  - Debris disks, looking for clumpiness due to planets
- **Characterize Extra-solar Giant Planets**
  - Characterize atmospheres with R=20 spectroscopy
  - Observe secular changes in spectrum
  - Observe orbit of the planet
  - Estimate density of planet, determine if rocky or gaseous
  - Determine main constituents of atmospheres
- **Star formation**
  - Evolution of circumstellar disks, morphology, gaps, rings
- **Extragalactic astronomy**
  - AGN nuclei

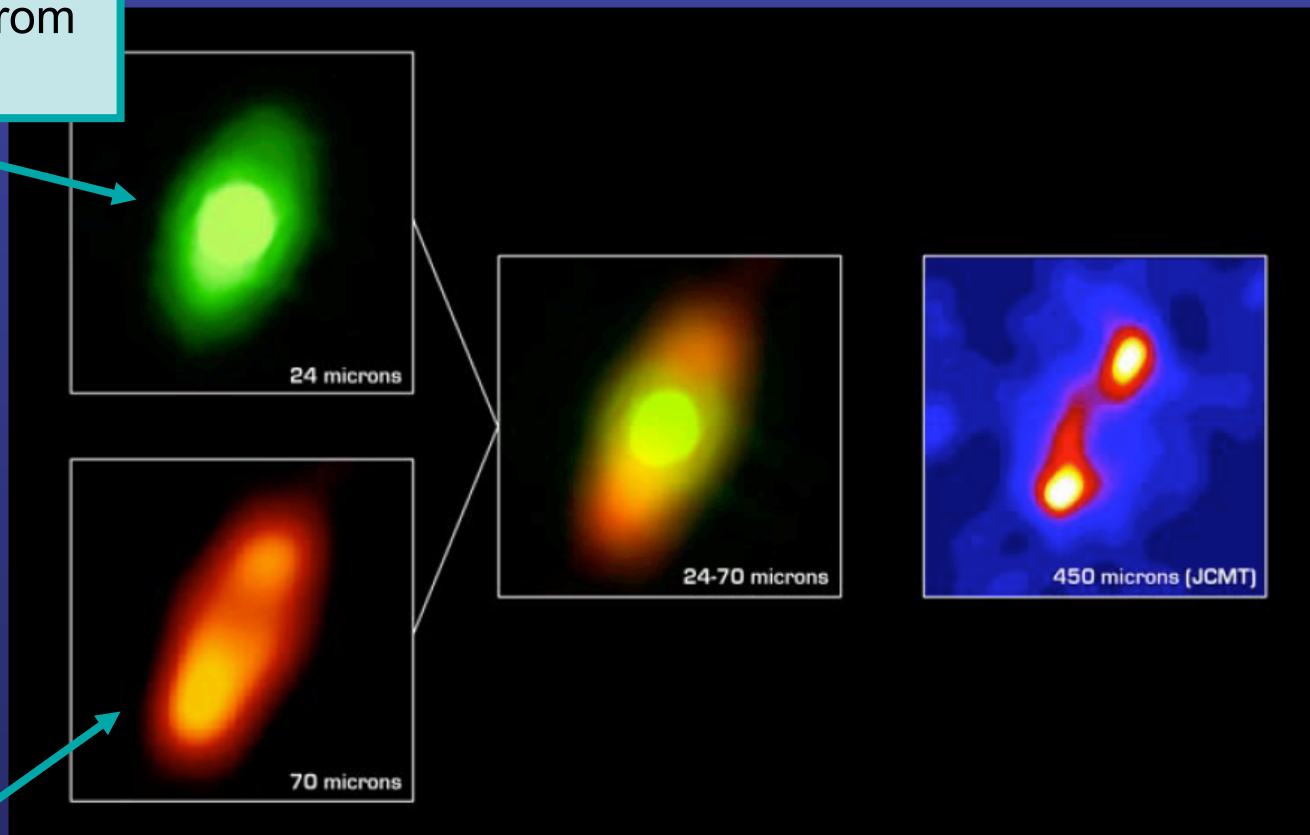
New Image of Fomalhaut b



Credit: NASA, ESA, P. Kalas, J. Graham, E. Chiang, and E. Kite (University of California, Berkeley), M. Clampin (NASA Goddard Space Flight Center, Greenbelt, Md.), M. Fitzgerald (Lawrence Livermore National Laboratory, Livermore, Calif.), and K. Stapelfeldt and J. Krist (NASA Jet Propulsion Laboratory, Pasadena, Calif.

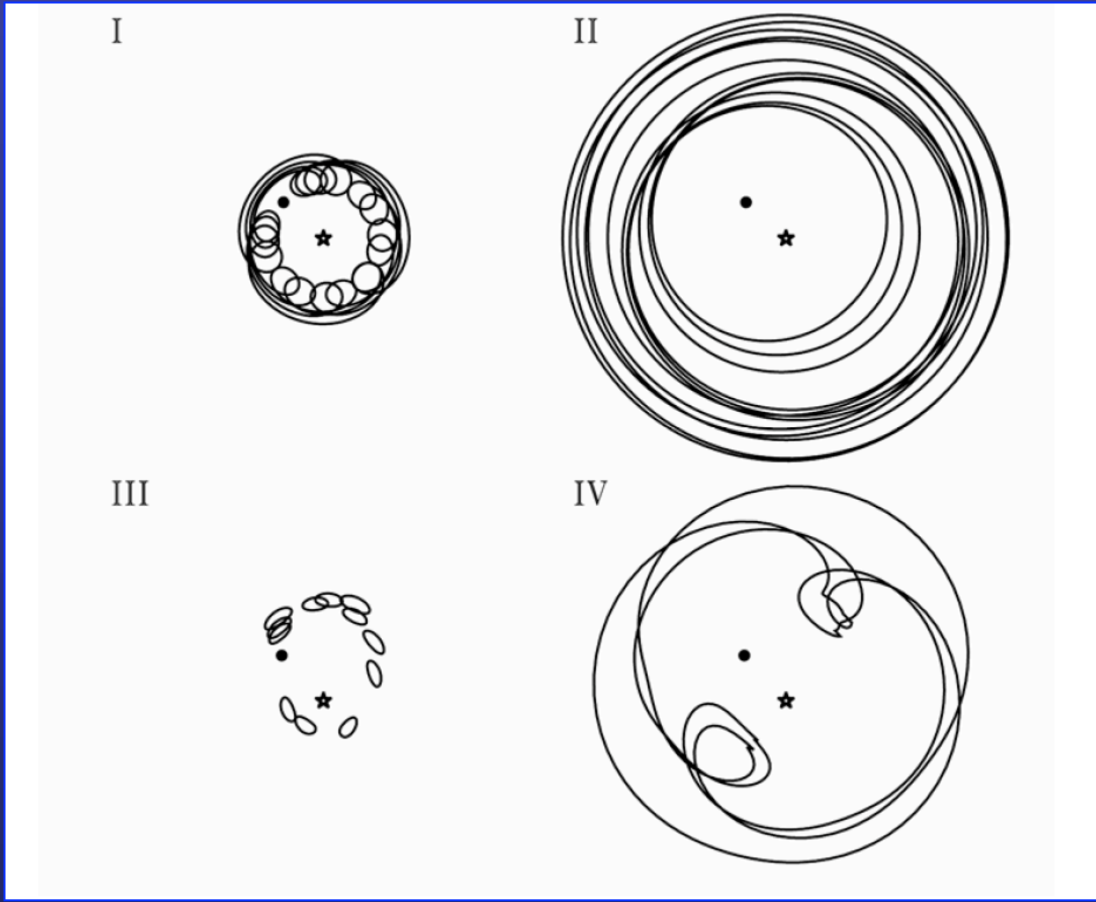
Large Scale Structure of Outer Debris Disk
Fomalhaut -- Spitzer

Emission from warm dust



Note asymmetry at 70 microns

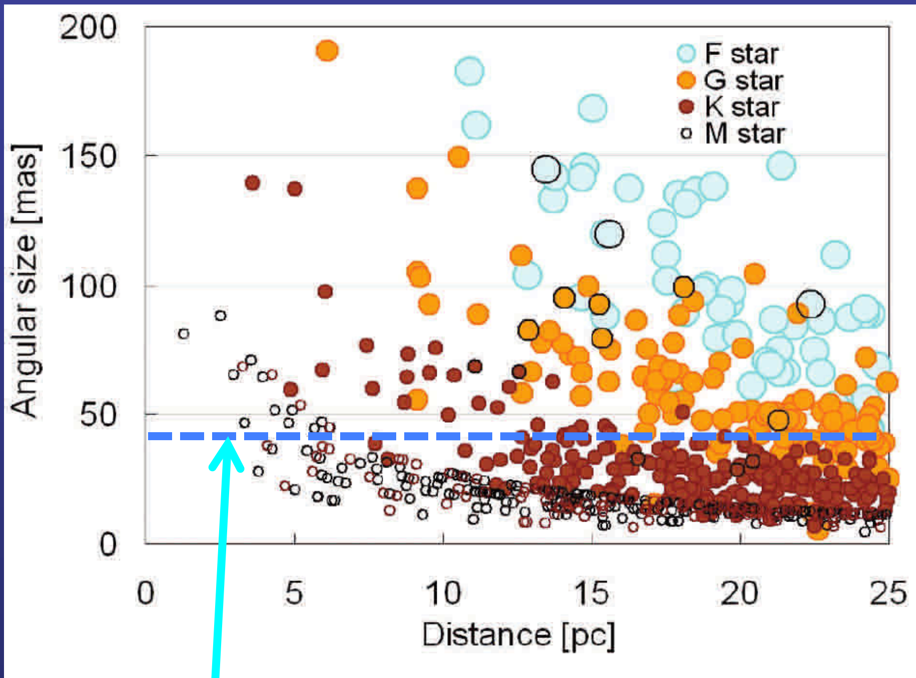
Debris Disk Resonant Structures
Theoretical expectations

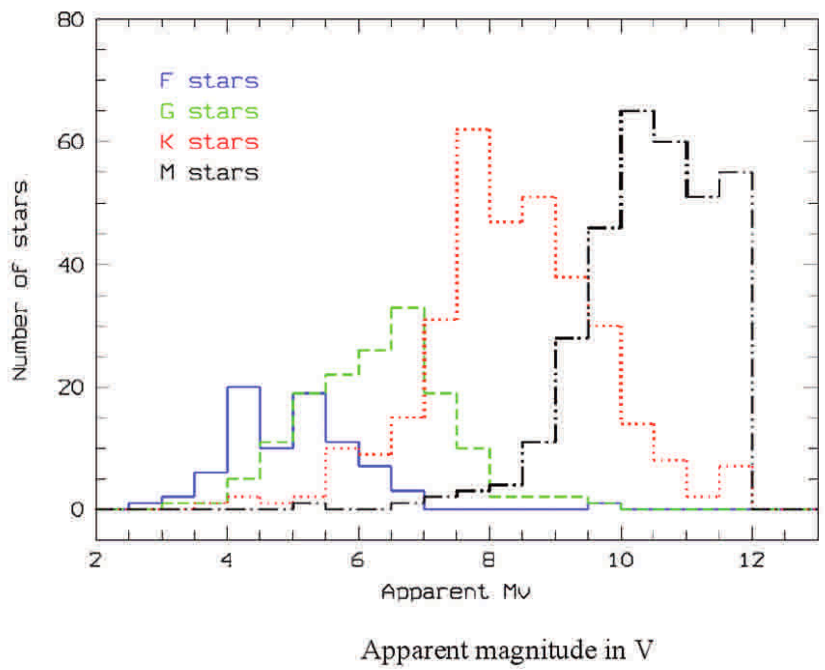


Kuchner & Holman 2003

TPF/Darwin Stars are FKSI Stars:

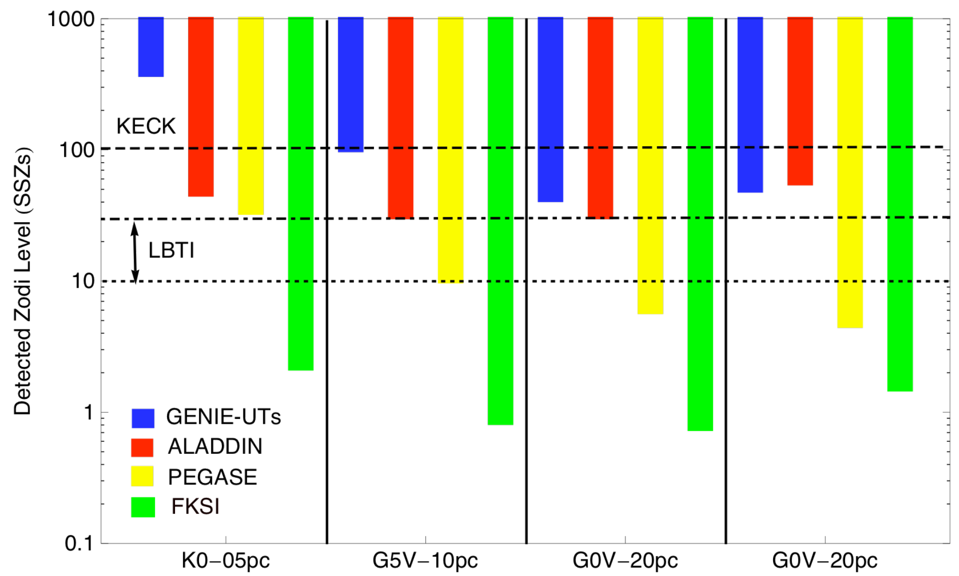
- 1256 single target stars and within 30 pc
  - 414 of which are M stars, 515 K stars, 218 G stars, and 109 F stars.
- Of the 1256 stars, 36 are known to host exoplanets.

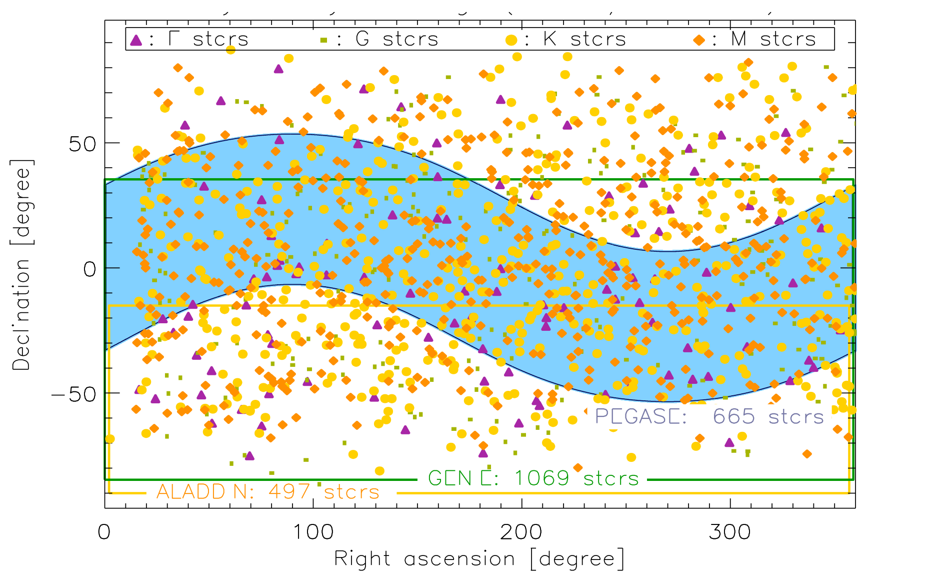




FKSI IWA ~ 40 mas,
Nearby F, G, K, M stars are all accessible

Debris Disk Sensitivity





Expected performance for Pegase and FKSI compared to the ground-based instruments (for 30 min integration time and 1% uncertainty on the stellar angular diameters).

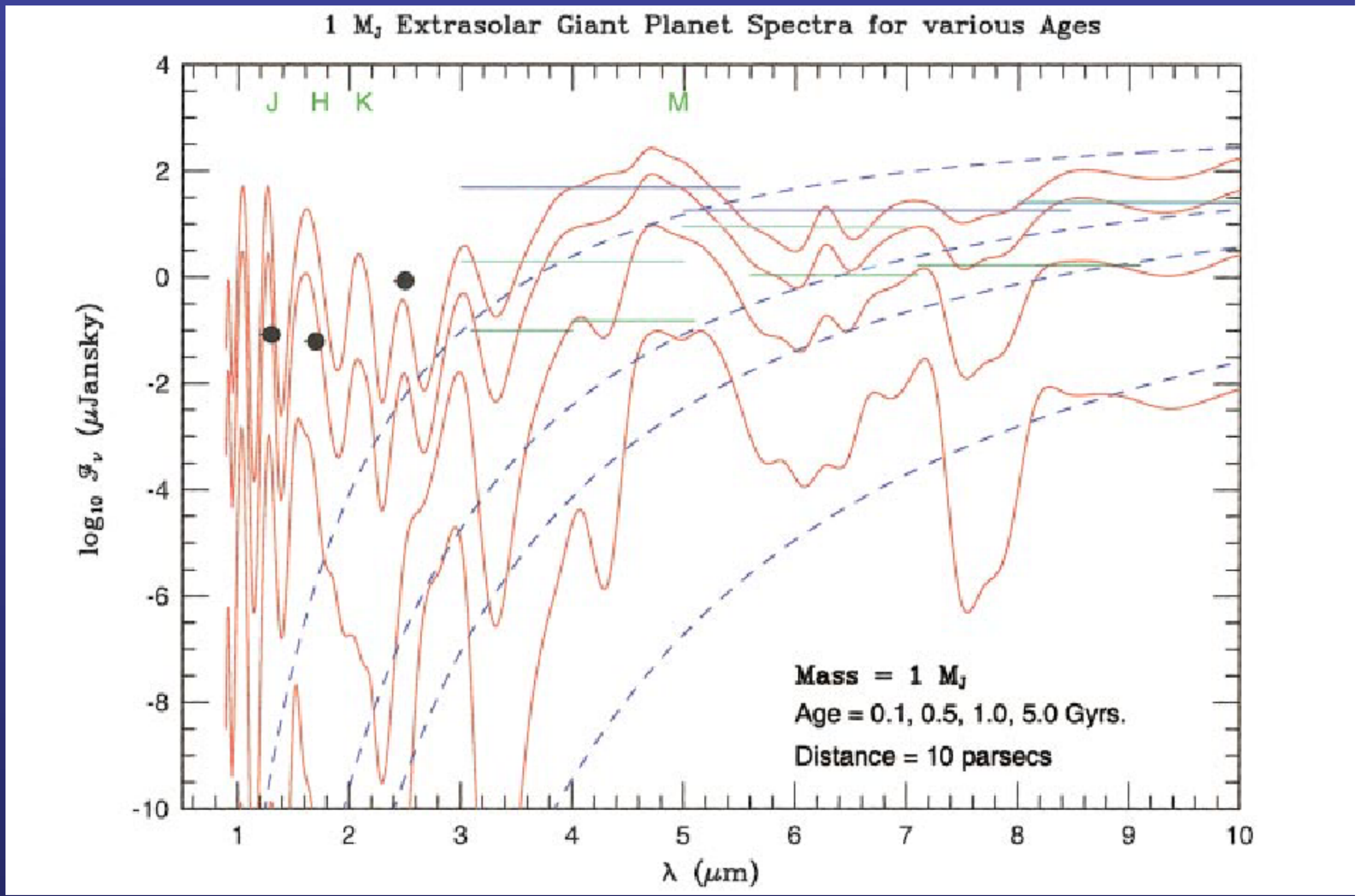
Sky coverage after 1 year of observation of GENIE (dark frame), ALADDIN (light frame) and Pegase (shaded area) shown with the Darwin/TPF all sky target catalogue. The blue-shaded area shows the sky coverage of a space-based instrument with an ecliptic latitude in the [-30˚, 30˚] range (such as Pegase). The sky coverage of FKSI is similar to that of Pegase with an extension of 40˚ instead of 60˚.

See Defrere et al. A&A (2008).

Extra Solar Giant Planet IR Spectrum as a Function of Age

The spectrum evolves with the age of the EGP. Spectral characteristics will help us determine the age and composition of their atmospheres.

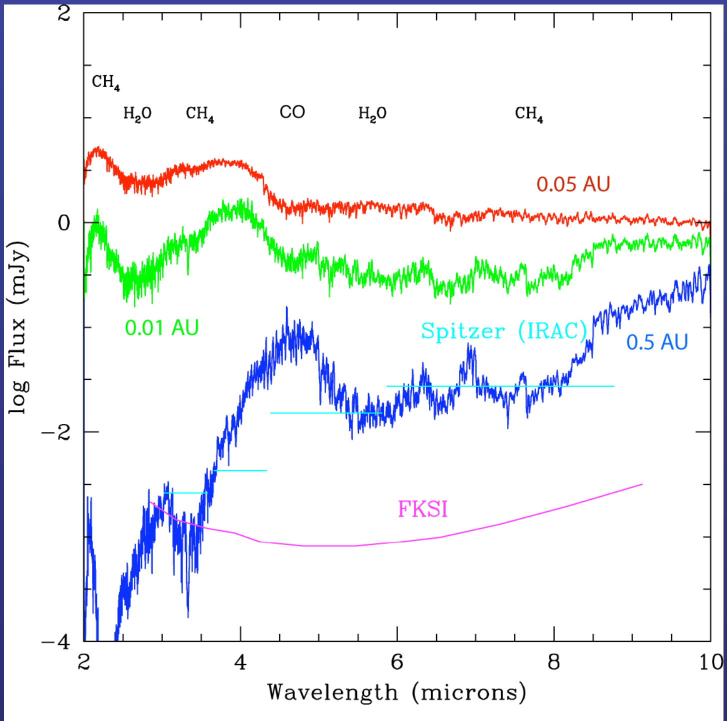
IR SPECTROSCOPY is the KEY to understanding exoplanets



From Burrows et al. 2001, RvMP

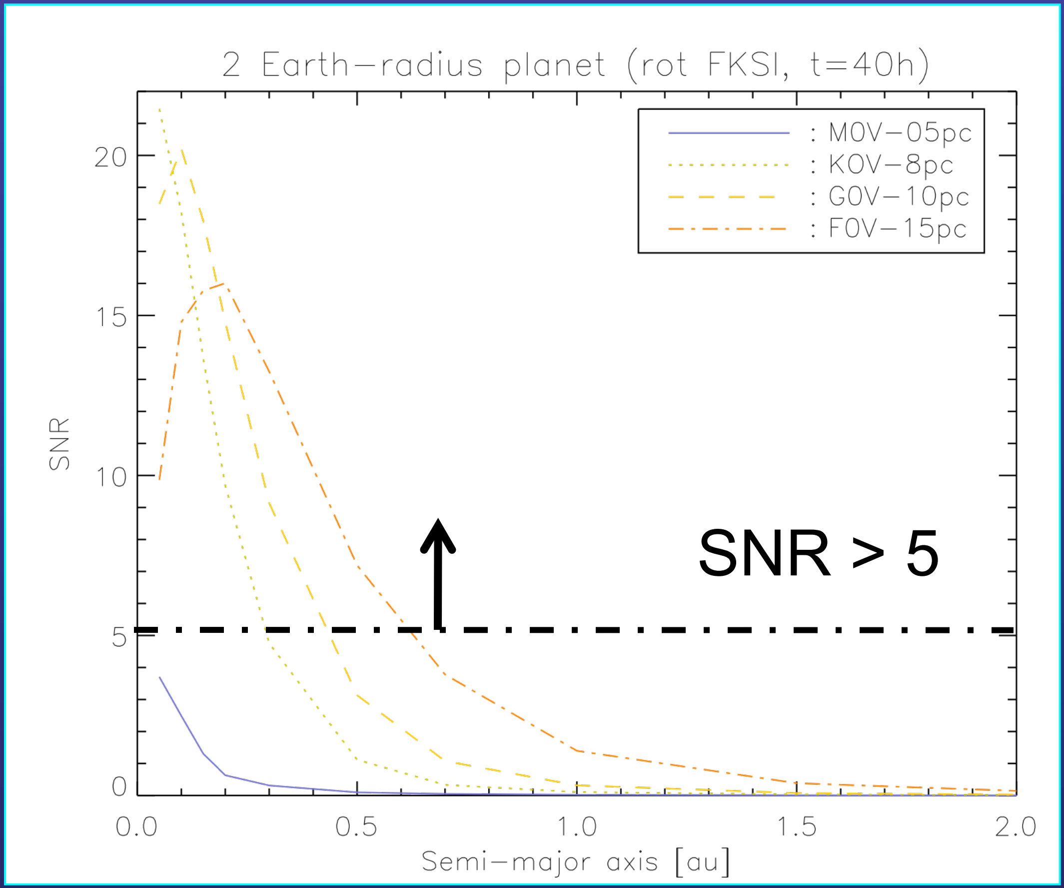
Exoplanet Characterization with a Small Structurally Connected Interferometer

Orbital Parameters	What FKSI does:
Removes sin(I) ambiguity	Measure
Planet Characteristics	
Temperature	Measure
Temperature variability due to distance changes	Measure
Planet radius	Measure
Planet mass	Estimate
Planet albedo	Cooperative
Surface gravity	Cooperative
Atmospheric and surface composition	Measure
Time variability of composition	Measure
Presence of water	Measure
Solar System Characteristics	
Influence of other planets, orbit coplanarity	Estimate
Comets, asteriods, zodiacal dust	Measure



Left panel. Characteristics of exoplanets that can be measured using FKSI. (b) Right panel. The FKSI system can measure the spectra of exoplanets with a wide range of semi-major axes.

Sensitivity to 2 R_{Earth} Super-Earths



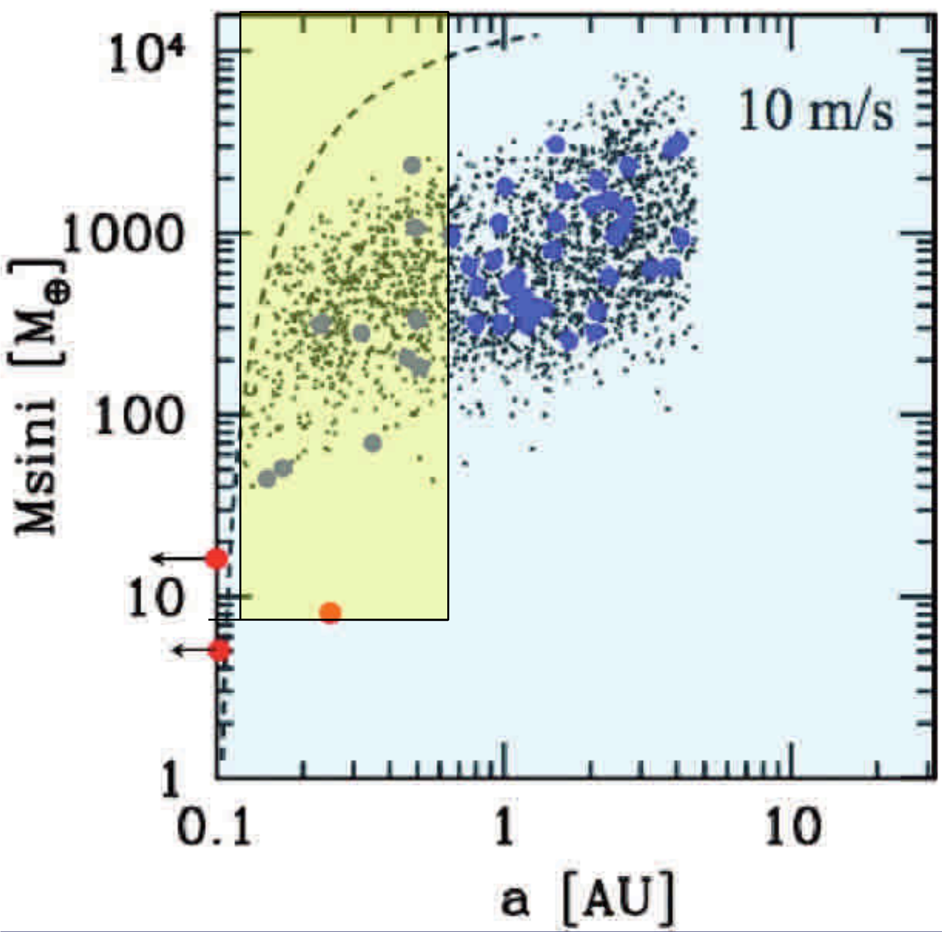
SNR > 5

- F0V R<0.65 AU
- G0V R<0.5 AU
- K0V R<0.3 AU

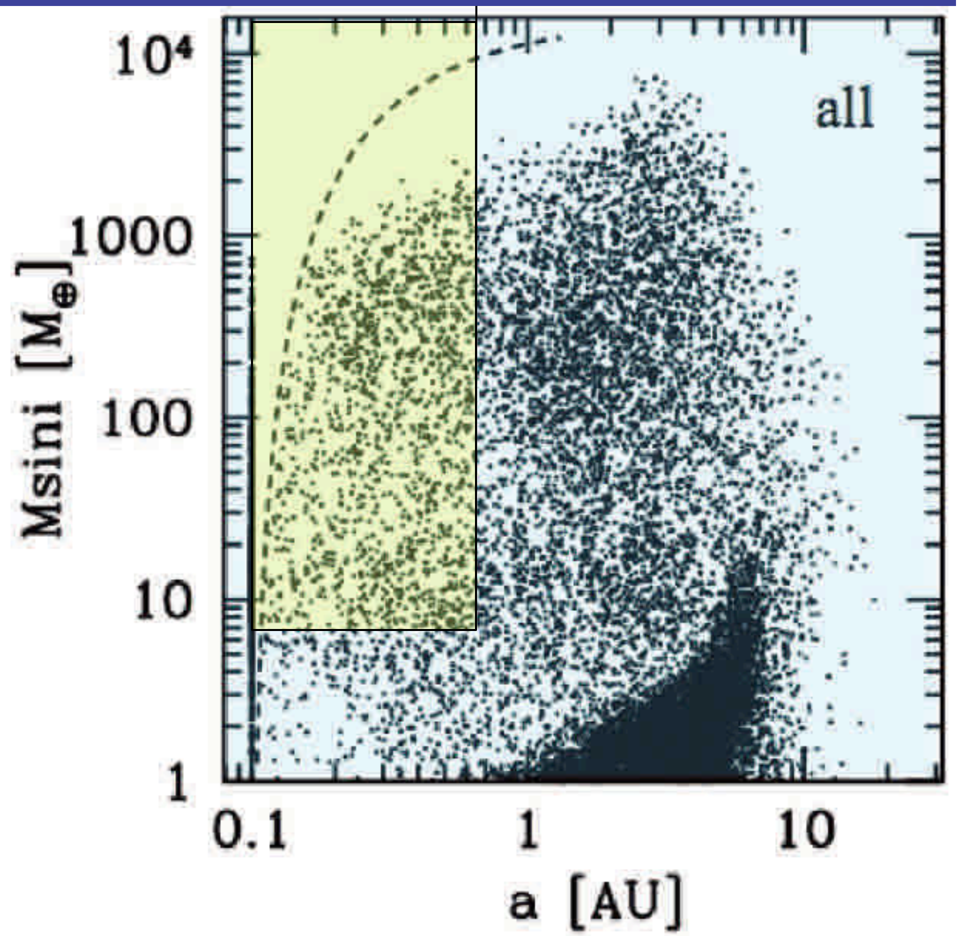
Defrere et al. 2009

Discovery Space For Super Earths

Large Planets

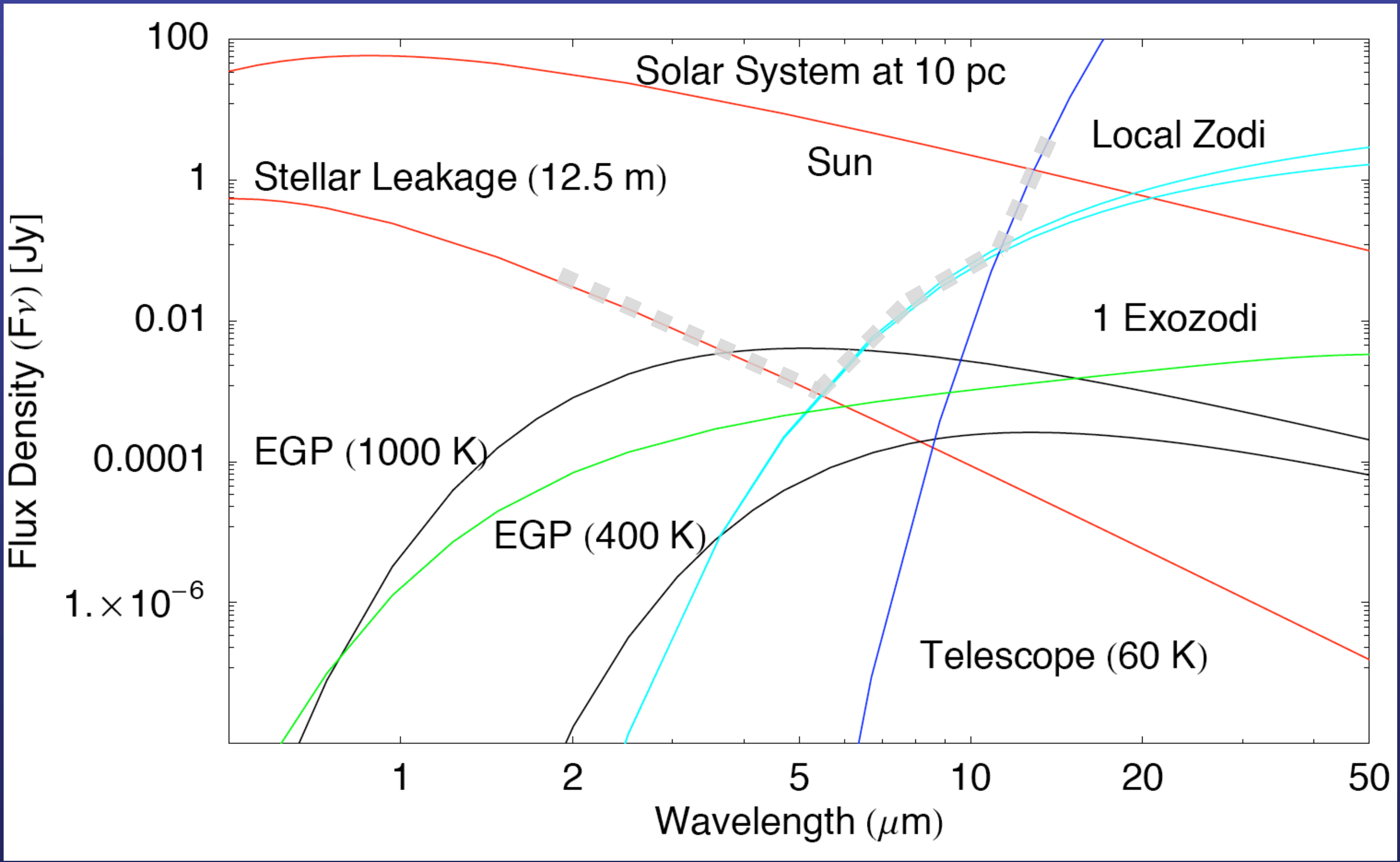


Terrestrial Planets

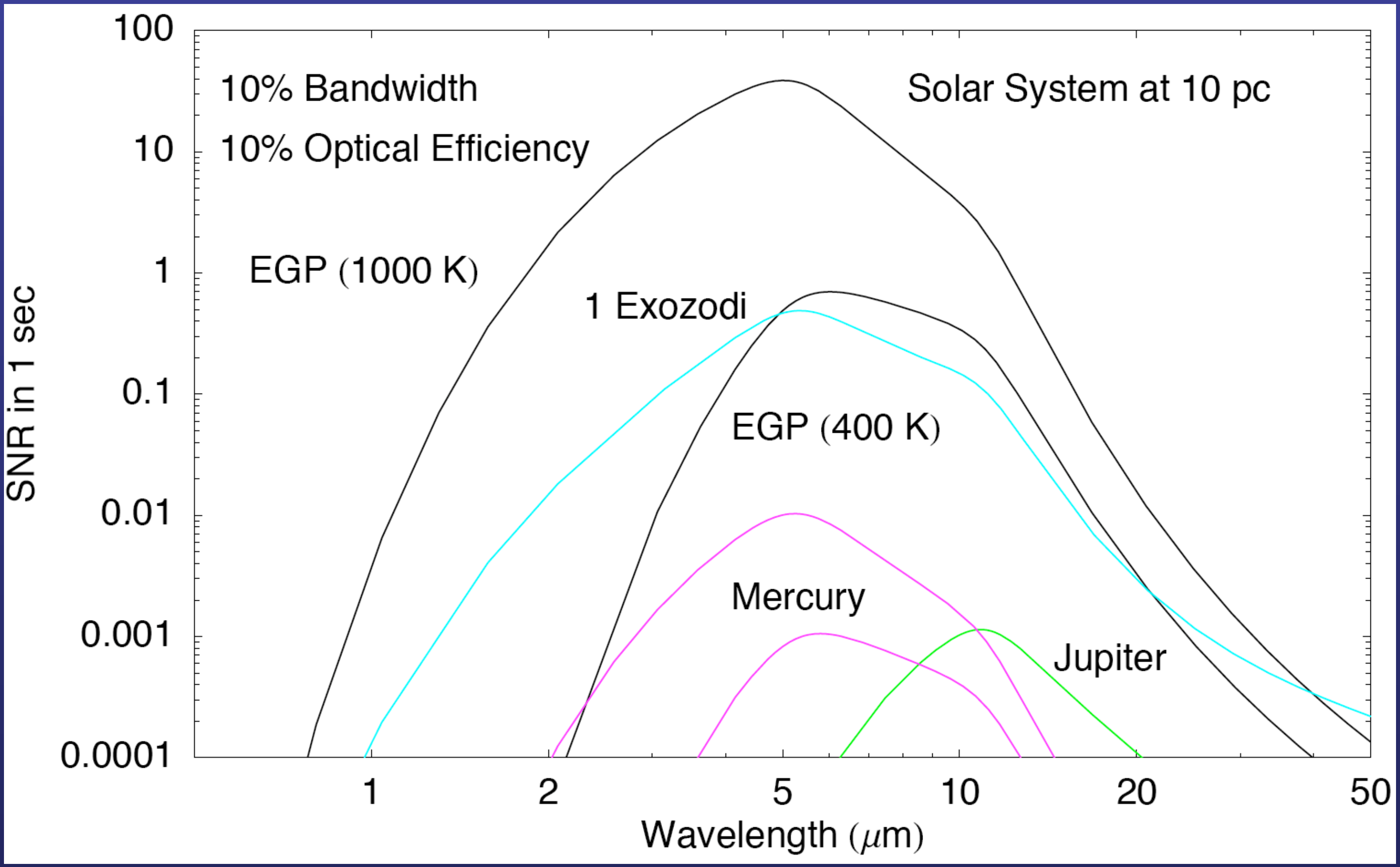


Extended core-accretion models (Alibert *et al., 2005) can* now be used to compute synthetic planet populations, which allows for a statistical comparison with observations (Ida and Lin, 2004; Benz *et al., 2007). Figure on the left displays blue dots for predicted giant planets, figure on right is for terrrestrial planets.*

Noise and Signal Source Flux Densities



Signal-to-Noise in 1 s for 1 m^2 collecting area



FKSI Requirements Flowdown

Science Goals

- Characterize Extrasolar Giant Planet Atmsopheres
- Measure resonant disk structures in exo-zodiacal debris disks to find and characterize extrasolar planets
- Understand evolution of young stellar systems and their planet forming potential
- Measure detailed structures inside active galactic nuclei

→

Measurement Capabilities

Near-IR and Mid-IR Imaging and Spectroscopy

Spectral Range

~3-8 µm

Angular Resolution

~ 41 (λ/5) mas

Spectra Resolving Power

λ/Δλ ~ 25

Field of View

~ 1-2 arcsec

Sensitivity

< 2 µJy continuum

Observations

At least one target field per day

→

Engineering Implications

Optical System and Metrology

•2 light collectors plus nulling beam combiner and spectrometer

•Baseline ~12 m

•~0.5-1 m diameter collector mirrors

•65 K optics
~ λ/10 rms at 632 nm

•Delay line metrology
~ 3 nm

•~15 nm rms pathlength control requirement

•Sub-arcsecond relative pointing

Detectors

< 10 e-/s dark current
< 10e- read noise
~128^2 pixels

Orientation

•Able to view >+/- 20° from ecliptic

→

Key Technologies

Detectors

•Very low dark current

•Very low read noise

•~35 K operating temperature desired

Active and Passive Cooling

•Efficient high-capacity cryocoolers

•~30 K cryocoolers

•Deployable mult-layer sunshades

Structures and mechanisms

•Deployable truss with light collectors

Interferometry

•Cryogenic high precision delay line

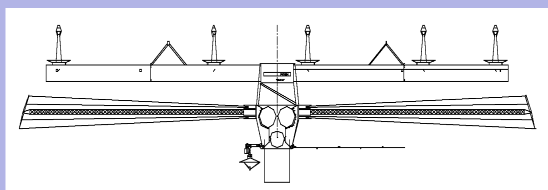
•Cryogenic optical fibers for beam cleanup

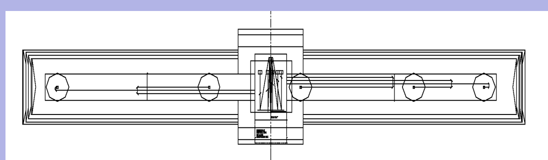
FKSI Mission Design Evolution

- GSFC actively developed FKSI mission designs since fall of 2001 with an intensive effort since August 2002
  - Targeted upcoming Discovery AO
- Mission design moved through A, B, and C iterations as costs were evaluated and as FKSI PI and Science Team refined science goals
  - "A" Design focused on a broad mission including general infrared astrophysical imaging at high angular resolution (20 m baseline), nulling, and low resolution spectroscopy (5 -- 1 m telescopes, 5-28 micron wavelength region)
  - "B" Design focused on a minimal version of the A system (3 – 1 m telescopes, 5-28 micron region, minimal sunshade)
  - "C" Design focused on nulling in 3-8 micron region (could be up to 10 or 12 microns, depending on detectors), and low resolution spectroscopy (2 -- 0.5 m telescopes, moderate sunshade)

FKSI Mission Trade Space Explored

"A" Design





No. of Telescopes: 5

Max. Baseline: 20 m (4-fold boom)

Sci. Spectral Range: 5 - 28 microns

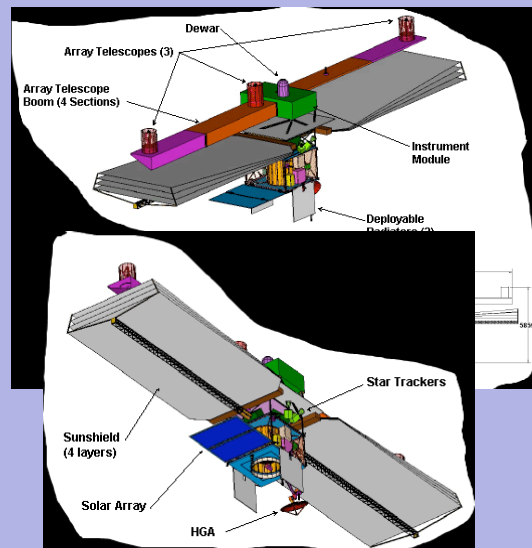
Interferometer Type: Fizeau (image plane)

Instrument Elements: Angle Tracker
Fringe Tracker
Imaging FTS
Nuller

Implementation: Two 6K adv. tech. mech. coolers, four 40K mech. coolers, sun shade separate from instrument, requires 5m LV fairing

Cost:

"B" Design



No. of Telescopes: 3

Max. Baseline: 16 m (4-fold boom)

Sci. Spectral Range: 5 - 28 microns

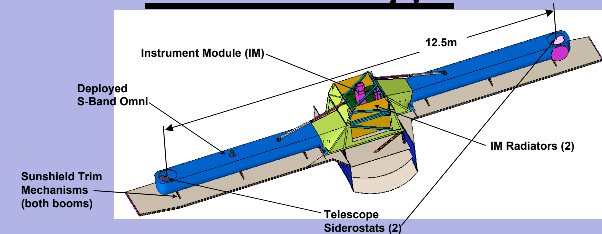
Interferometer Type: Fizeau (image plane)

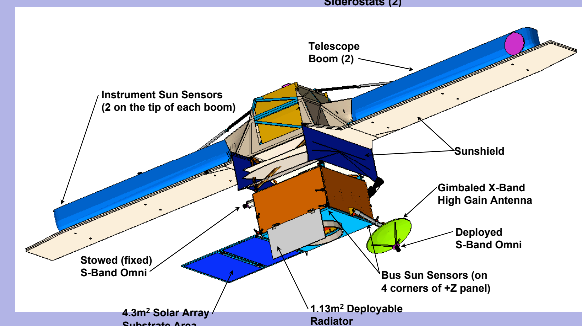
Instrument Elements: Angle Tracker
Fringe Tracker
Imaging FTS
(R=10,000)
Nuller

Implementation: 6K solid H2 cryostat + two 30K mech. coolers, sun shade separate from instrument, requires 5m LV fairing

Cost:

"C" Design





No. of Telescopes: 2 (siderostat)

Max. Baseline: 12.5 m (2-fold boom)

Sci. Spectral Range: 3 - 8 microns

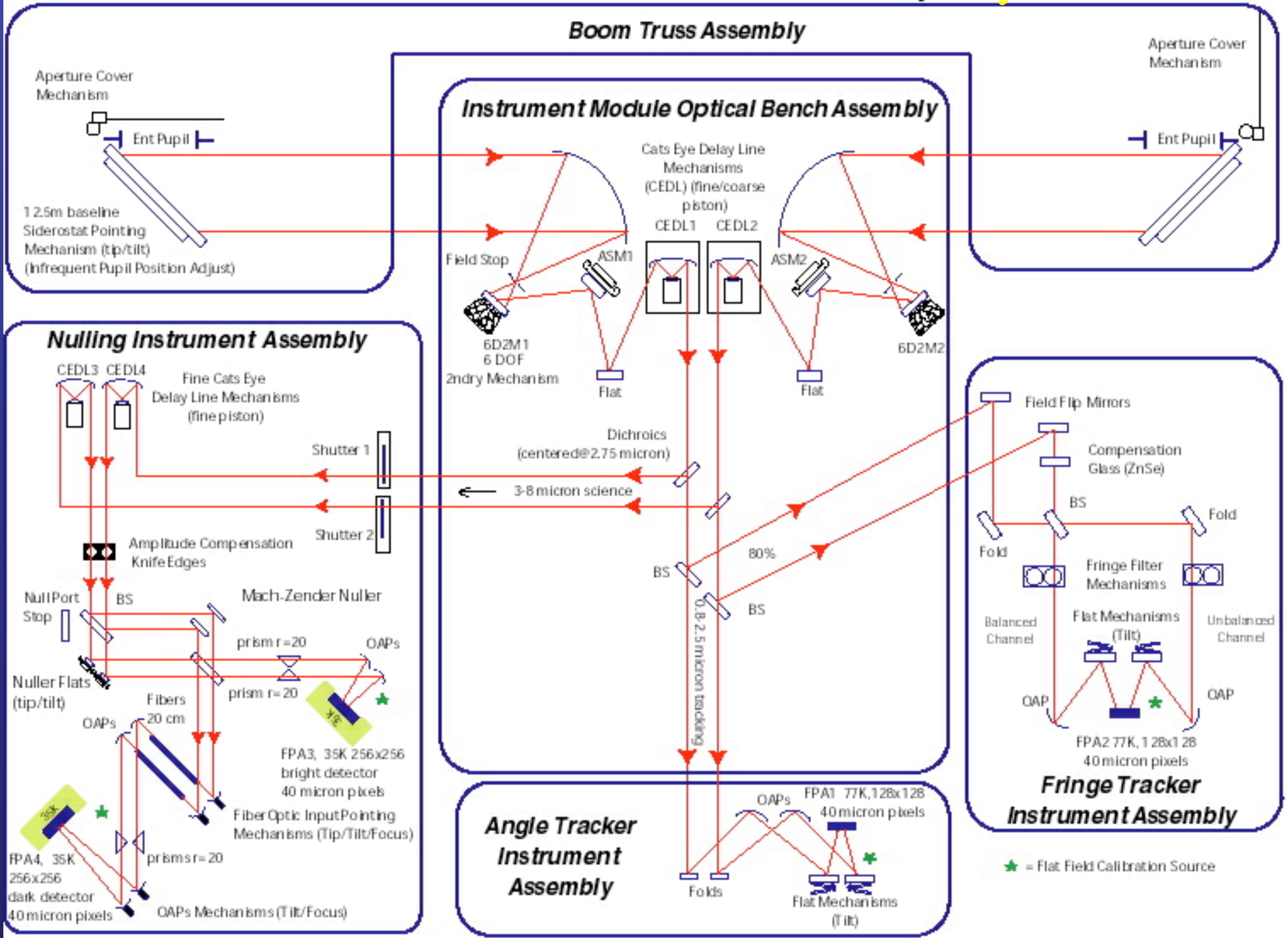
Interferometer Type: Michelson (pupil plane)

Instrument Elements: Angle Tracker
Fringe Tracker
Nuller w/ R=20

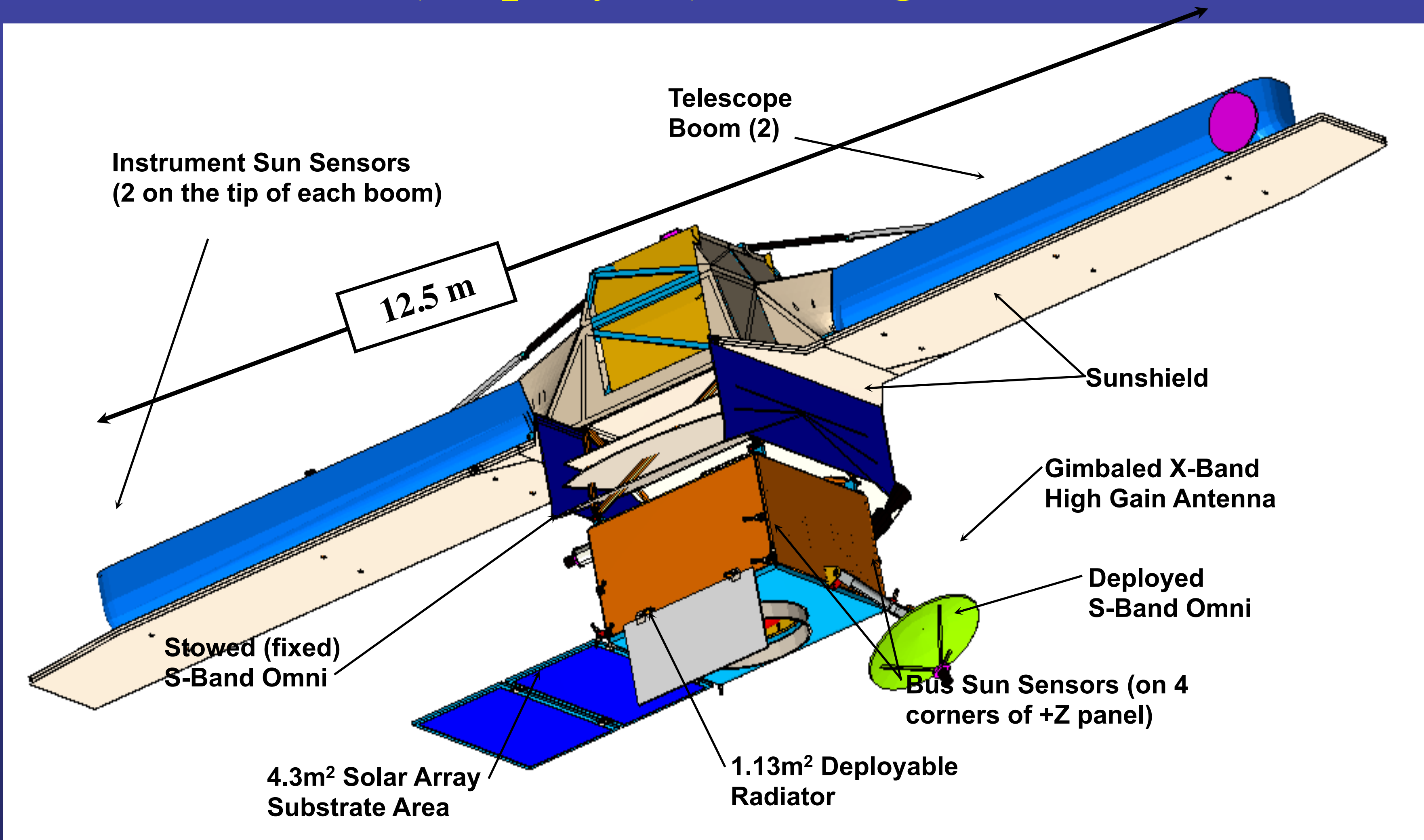
Implementation: One 32K mech. cooler, sun shade tied to instrument, fits in 4m LV fairing

Cost:

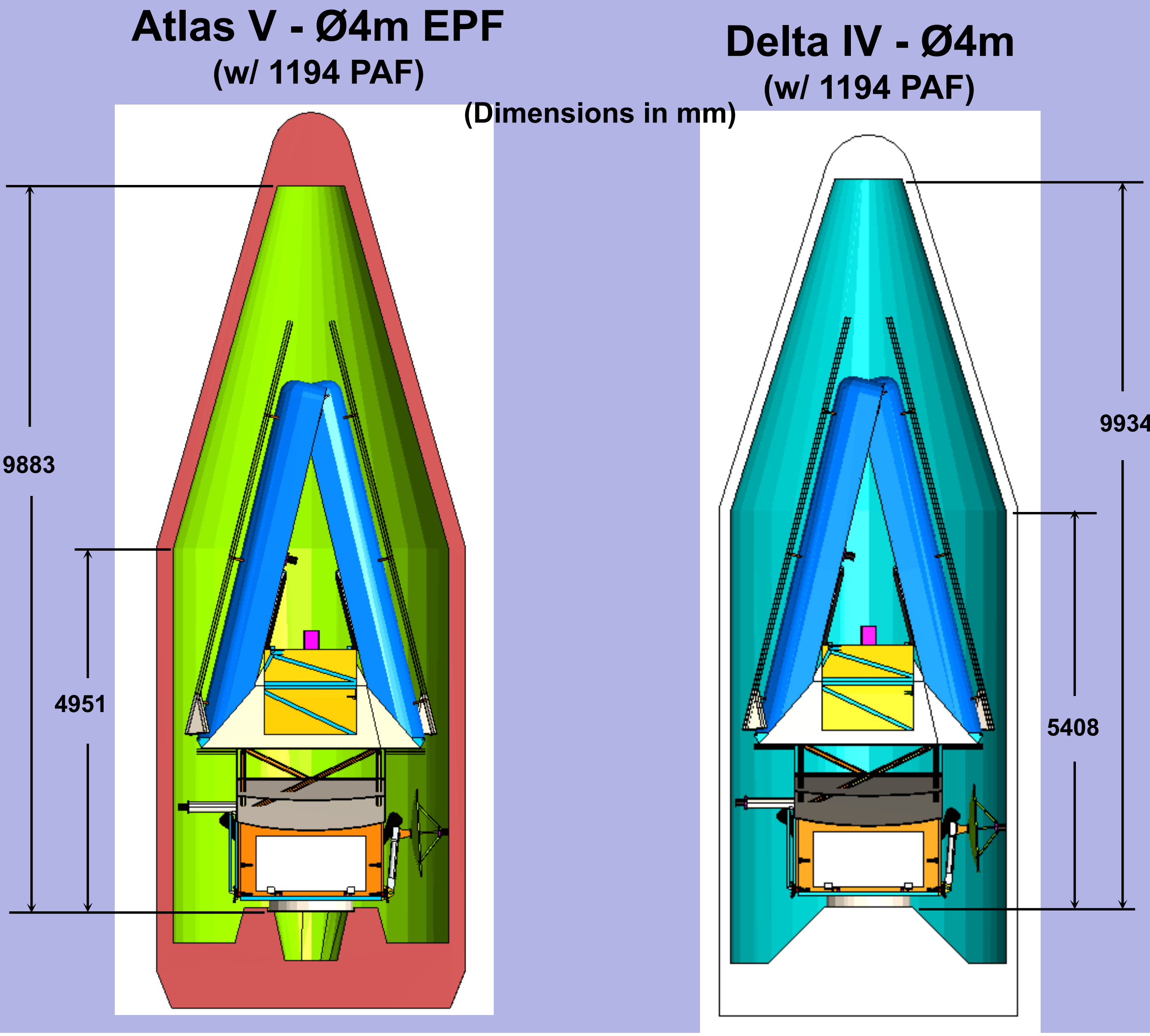
FKSI Instrument Module and Boom Subsystem



FKSI Observatory in Operational (Deployed) Configuration



Launch Vehicle Fairing Comparison
Static Envelope

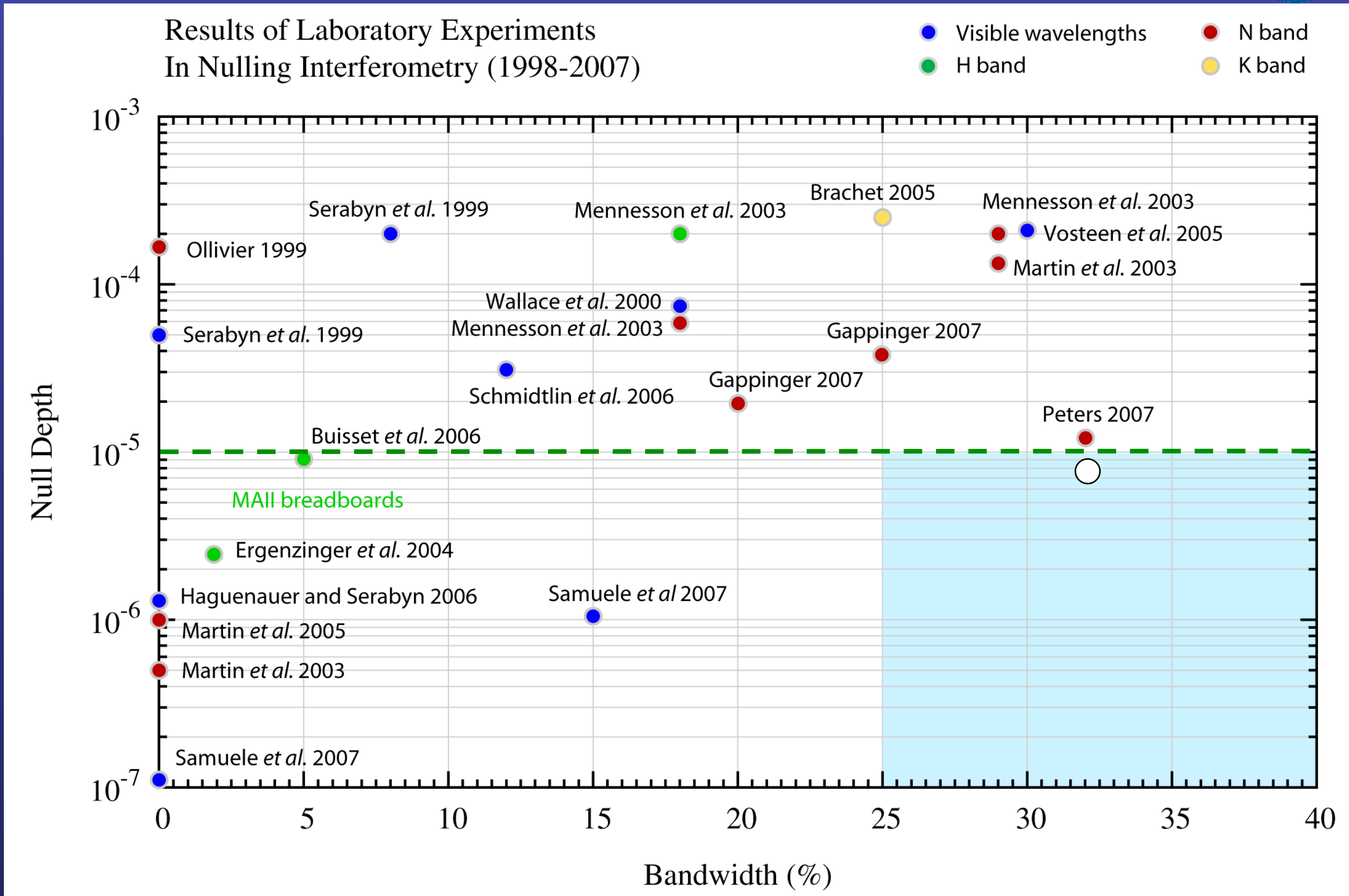


Technical Readiness for a Small Structurally Connected Interferometer

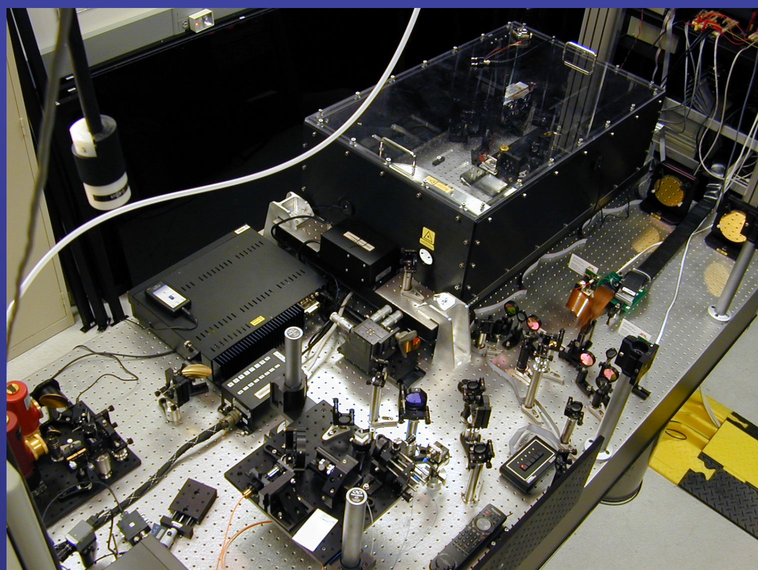
Item	Description	TRL	Notes
1	Cryocoolers	6	Source: JWST
2	Precision cryogenic structure (booms)	6	Source: JWST
3	Detectors (near-infrared)	6	Source: HST, JWST Nircam
4	Detectors (mid-infrared)	6	Source: Spitzer IRAC, JWST MIRI
5	Cryogenic mirrors	6	Source: JWST
6	Optical fiber for mid-infrared	4	Source: TPF-I
7	Sunshade	6	Source: JWST
8	Nuller Instrument	5	Source: Keck Interferometer Nuller, TPF-I project, LBTI
9	Precision cryogenic delay line	6	Source: ESA Darwin

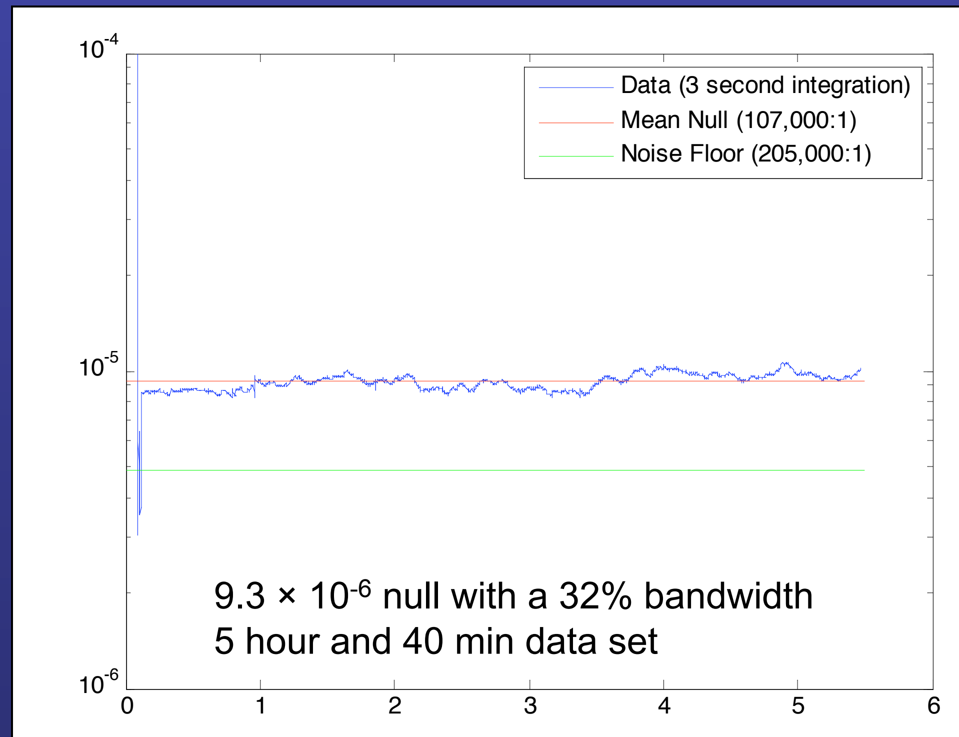
*Note: The requirement for the FKSI project is a null depth of 10^{-4} in a 10% bandwidth. Laboratory results with the TPF-I testbeds have exceeded this requirement by an order of magnitude (Lawson et al. 2008).

State of the Art in Broadband Nulling



Milestone #1: Phase & Amplitude Control
Milestone #3: Broadband Nulling





Goal: Mid-infrared nulling with mean null depth of 1×10^{-5} using a 25% bandwidth centered at 10 microns; three 6-hour experiments. (Whitepaper signed, 10 October 2007)

World record broadband mid-IR null, exceeds flight requirements

Rejection Ratio
161339 :1

Intensity imballance
0.11 %

Phase Dispersion
4.8 nm

Path Control
3.54 nm

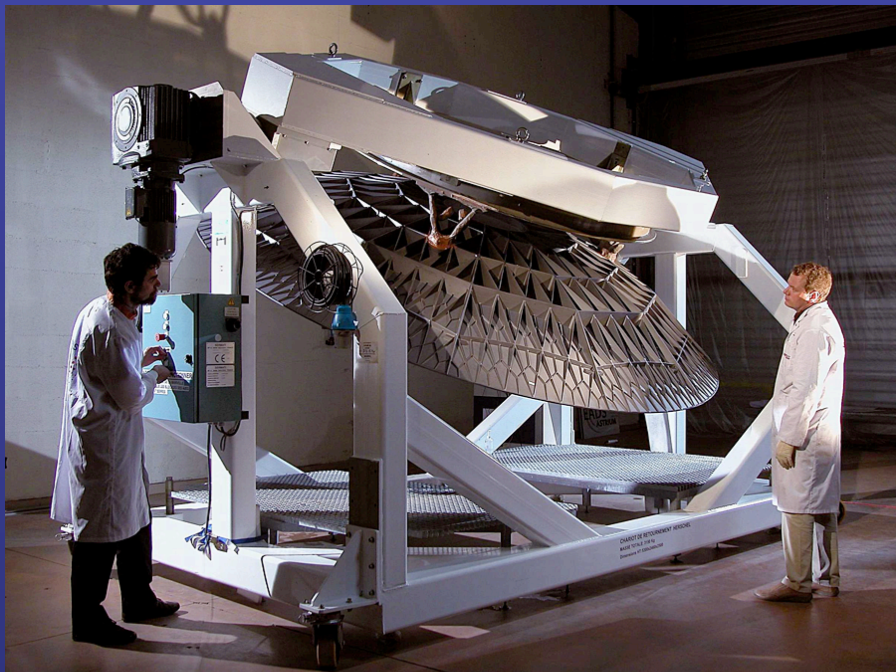
Birefringence
0 nm

Pupil Rotation
0 deg

Noise Floor
4.89E-06 V_norm

Large Light-Weight Optics

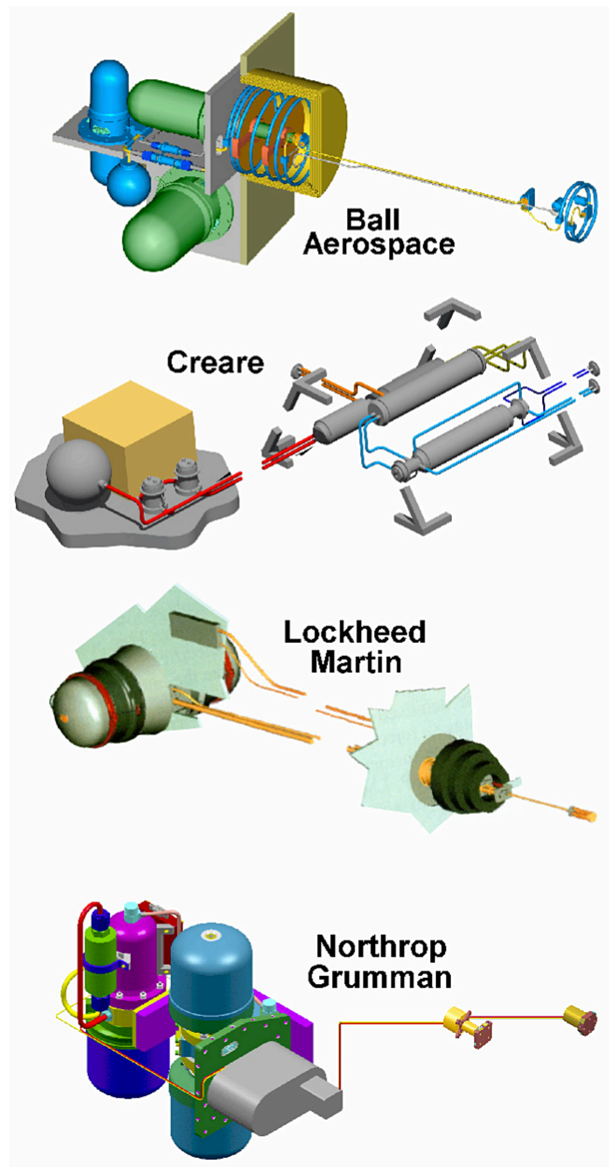
- Herschel Primary Mirror



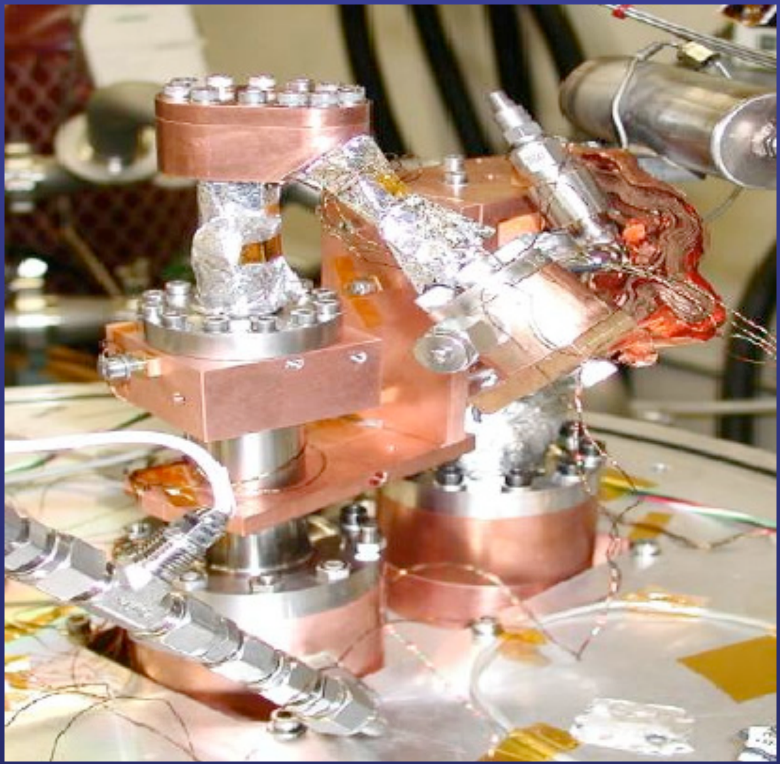
Passive Cryogenic Cooling

- JWST Sunshield

Cryocoolers

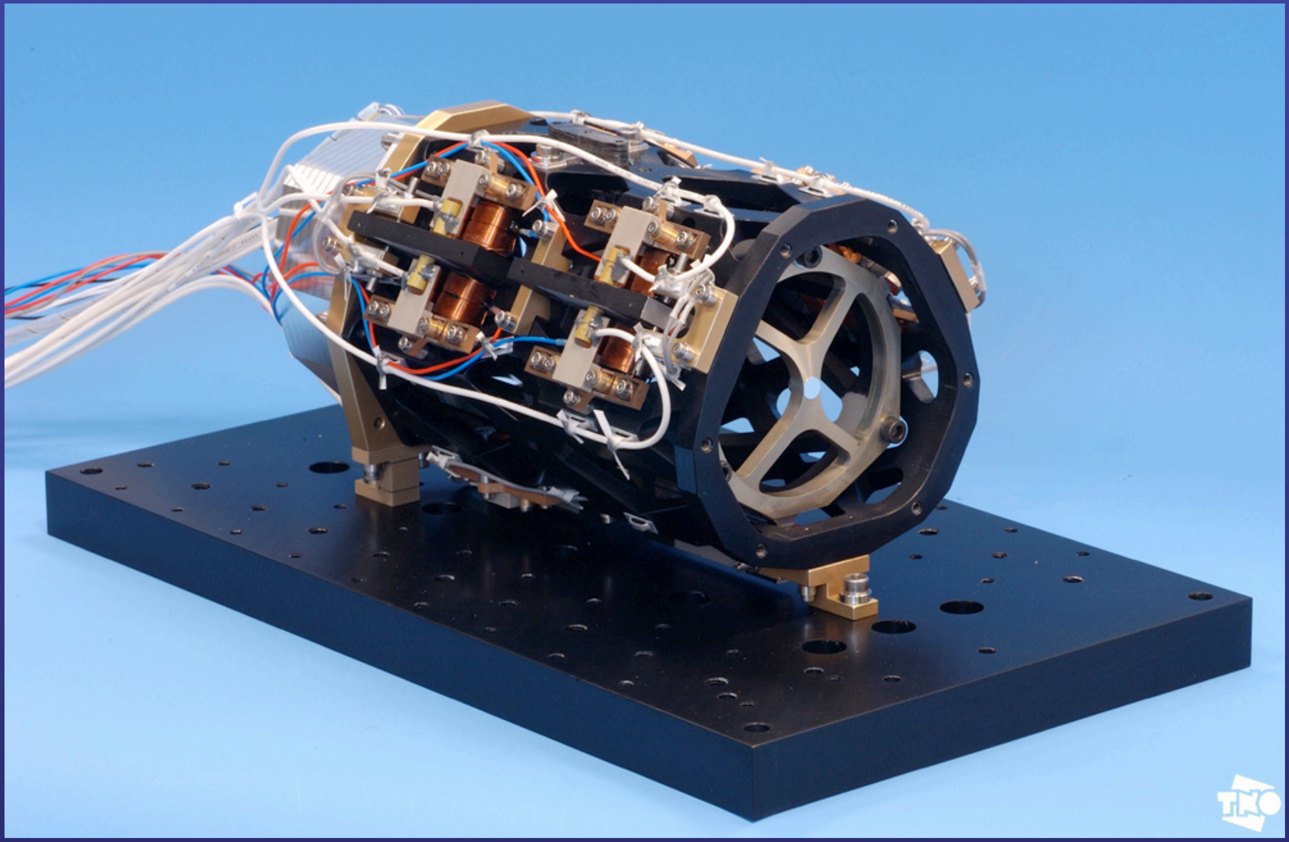


- Advanced Cryocooler Technology Development Program



- JWST Cryocooler (NGST)

Cryogenic Optical Path Compensation



- Prototype delay line for Darwin (ESA)

Schedule assuming FY11 start

	Activity Name	Start Date	Finish Date
1	Phase A Study	1/3/11	6/29/12
2	Phase B Start	6/25/12	
3	Mission PDR	7/1/14	
4	Mission CDR	7/1/15	
5	Mission Implementation	12/1/14	12/1/17
6	Mission Confirmation Review	12/1/14	
7	LAUNCH	12/1/17	
8	INSTRUMENT DEVELOPMENT	7/2/12	4/29/16
9	System Requirements Review	10/1/12	
10	Instrument PDR	7/22/13	
11	Instrument Flight Build	12/2/13	4/29/16
12	Instrument CDR	4/1/14	
13	SPACECRAFT DEVELOPMENT	1/28/13	9/30/16
14	Spacecraft PDR	6/28/14	
15	Spacecraft CDR	3/2/15	
16	GROUND SYSTEM DEVELOPMENT	4/1/13	12/1/17
17	Science Operations Center (SOC)	9/1/14	12/1/17
18	SOC PDR	9/1/14	
19	SOC CDR	5/1/15	
20	Mission Operations Center (MOC)	7/1/14	12/1/17
21	MOC PDR	7/1/14	
22	MOC CDR	12/1/14	
23	OPERATIONS	12/1/17	4/30/19
24	EXTENDED OPERATIONS	5/1/19	3/30/23

Cost Estimates

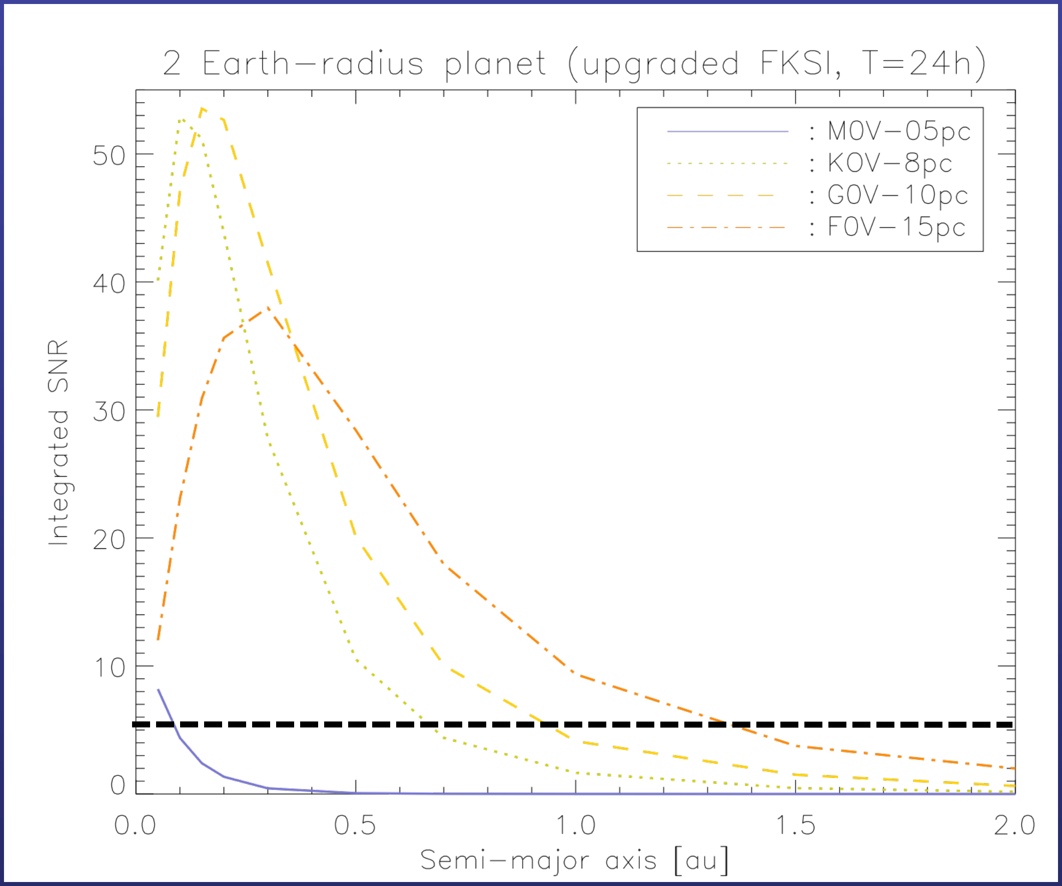
Over the years we have done grassroots, PRICE H, and Resource Analyst Office parametric estimates:

- *Cost is $635 M for a 2 year minimum science mission, including $160 M for LV*
- *Thus it is $475 M without LV, well below guidance of $600-800 M without LV*
- *This is at 50% probability on the "S" curve*
- *At 70%, cost estimate is $600 M without LV*

- We have around $100-200 M for mission growth while remaining within cost box.
  - *Desirable trades include increasing apertures to 1m, telescopes to 40K, and wavelength range from 5-15 um, baseline to 20 m.*

Upgraded FKSI Detects many more Super-Earths, R>2 R_{Earth}

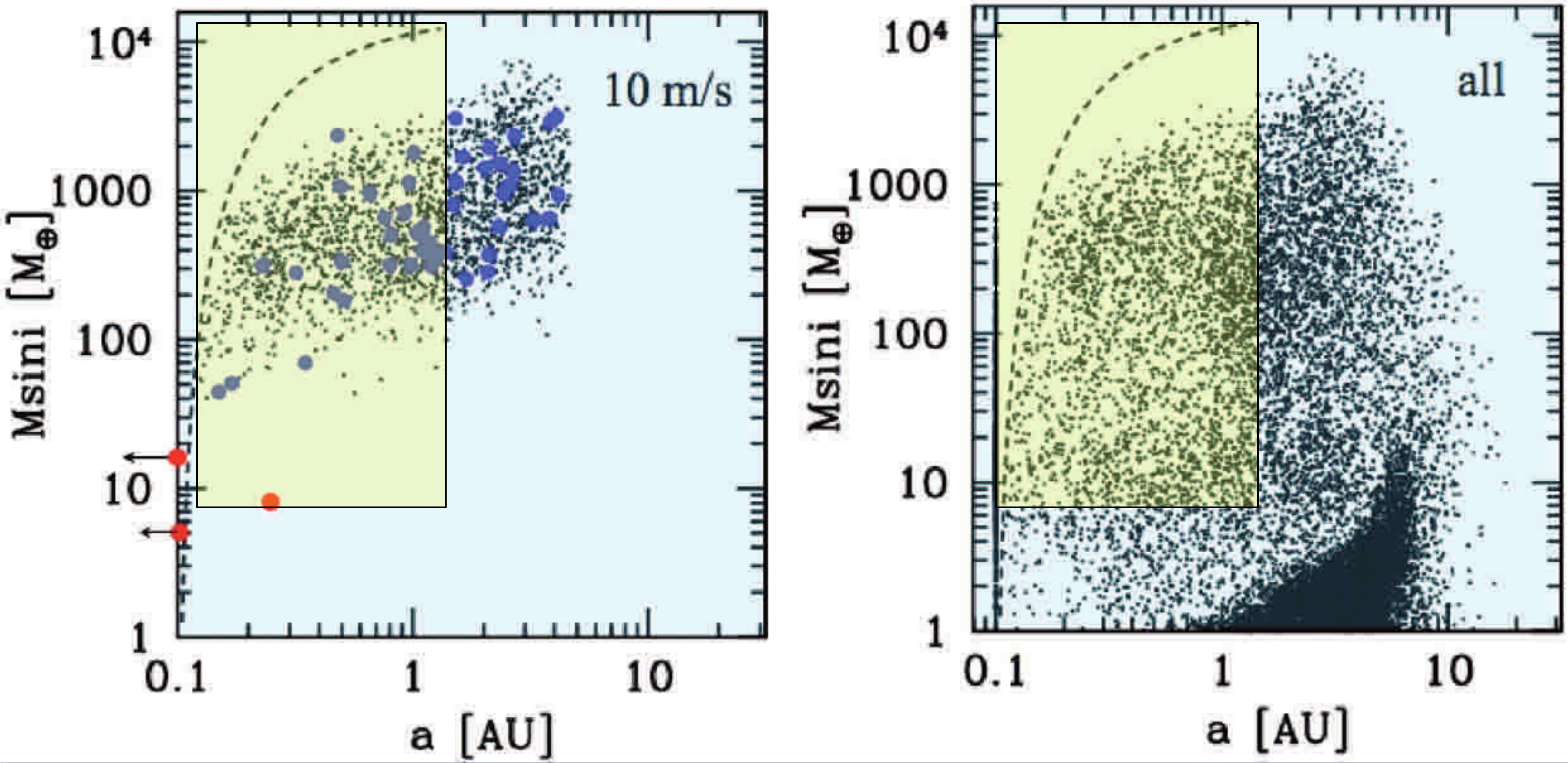
1 m apertures, 40K telescopes, 20 m baseline



SNR > 5

- F0V R<1.35 AU
- G0V R<0.95 AU
- K0V R<0.55 AU
- M0V R<0.1 AU

Enhanced Discovery Space For Super Earths with upgraded FKSI



Conclusions

- FKSI is an attractive mission
  - *It is well within the cost box*
  - *Most technologies are in hand, a few need further development to reach TRL 6*
  - *It completely resolves the exozodi issue*
  - *It characterizes known exoplanets*
  - *It has a large discovery space for super-earths*
  - *It has a much larger general astrophysics phase space than discussed here*
  - *With the wind at our backs, we might detect a few Earth-twins if they are common*
- Natural partnerships exist within Europe and US
  - *Includes NASA Centers such as GSFC, JPL, MSFC, ARC*
  - *Corporations such as BATC, NGST, …, Tinsley, …*
  - *Foreign partnership possibilities include CNES, ESA, JAXA, …*
  - *Universities and Laboratories such as MIT, UMd, TSU, UMich, UNice, IAP, IAS, OCA, LAOG, Open U., …*

•FUNDING is need to further develop the concept and optimize the science vs. mission cost. Technology development needed in just a few areas such as cryogenic testing of fibers and cryogenic nulling testbeds for system level tests. Could be done in Phase A.

Backup Slides

- Backup Slides

Cost Estimate Details

WBS Element	FY03 k$ Total	Inflated by 19.90%*	Phase A	Phase B	Phase C/D	Phase E	Total
Management System	$11,510	$13,800	$750	$2,760	$9,660	$1,380	$14,550
Engineering	$5,123	$6,142	$675	$1,535	$4,606		$6,817
SMA	$3,502	$4,199	$270	$1,050	$3,149		$4,469
Science	$8,407	$10,080	$675	$2,016	$3,528	$4,536	$10,755
Payload	$153,051	$183,509	$5,000	$45,877	$137,631		$188,509
Spacecraft	$85,462	$102,469	$2,500	$25,617	$76,852		$104,969
Operations	$10,533	$12,629				$12,629	$12,629
Launch Vehicle**	$104,100	$160,000			$160,000		$160,000
Ground System	$10,099	$12,109			$12,109		$12,109
System I&T	$8,545	$10,246			$10,246		$10,246
EPO	$3,321	$3,982			$1,991	$1,991	$3,982
TOTAL	**$403,653**	**$519,164**	**$9,870**	**$78,856**	**$419,772**	**$20,536**	**$529,034**
RESERVES* **			**$0**	**$23,657**	**$77,334**	**$5,564**	**$106,555**
GRAND TOTAL							**$635,589**

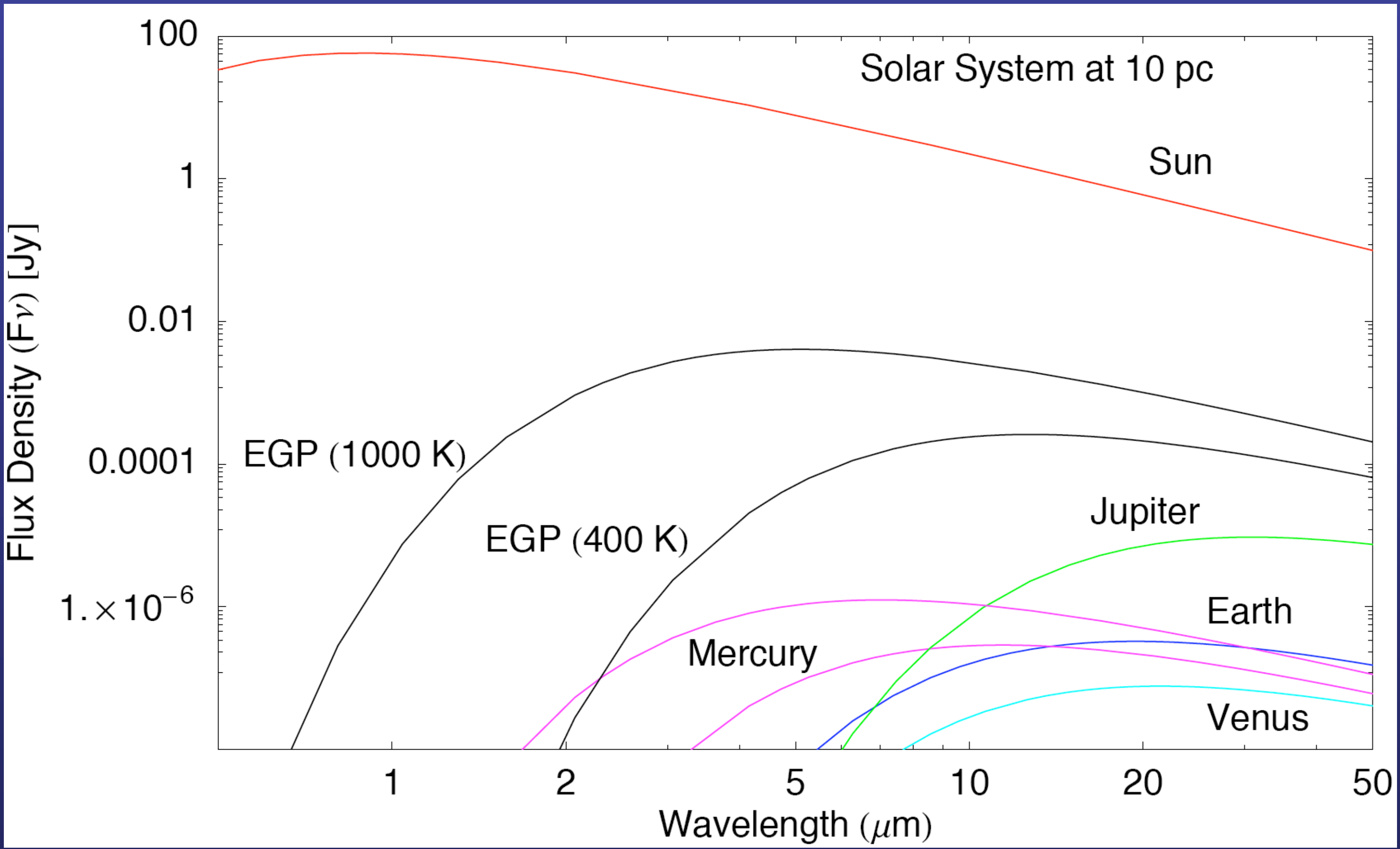
NB: Note that all costs are in units of $1000.

*The NASA inflation adjustment from FY03 to FY09 is 19.9%.

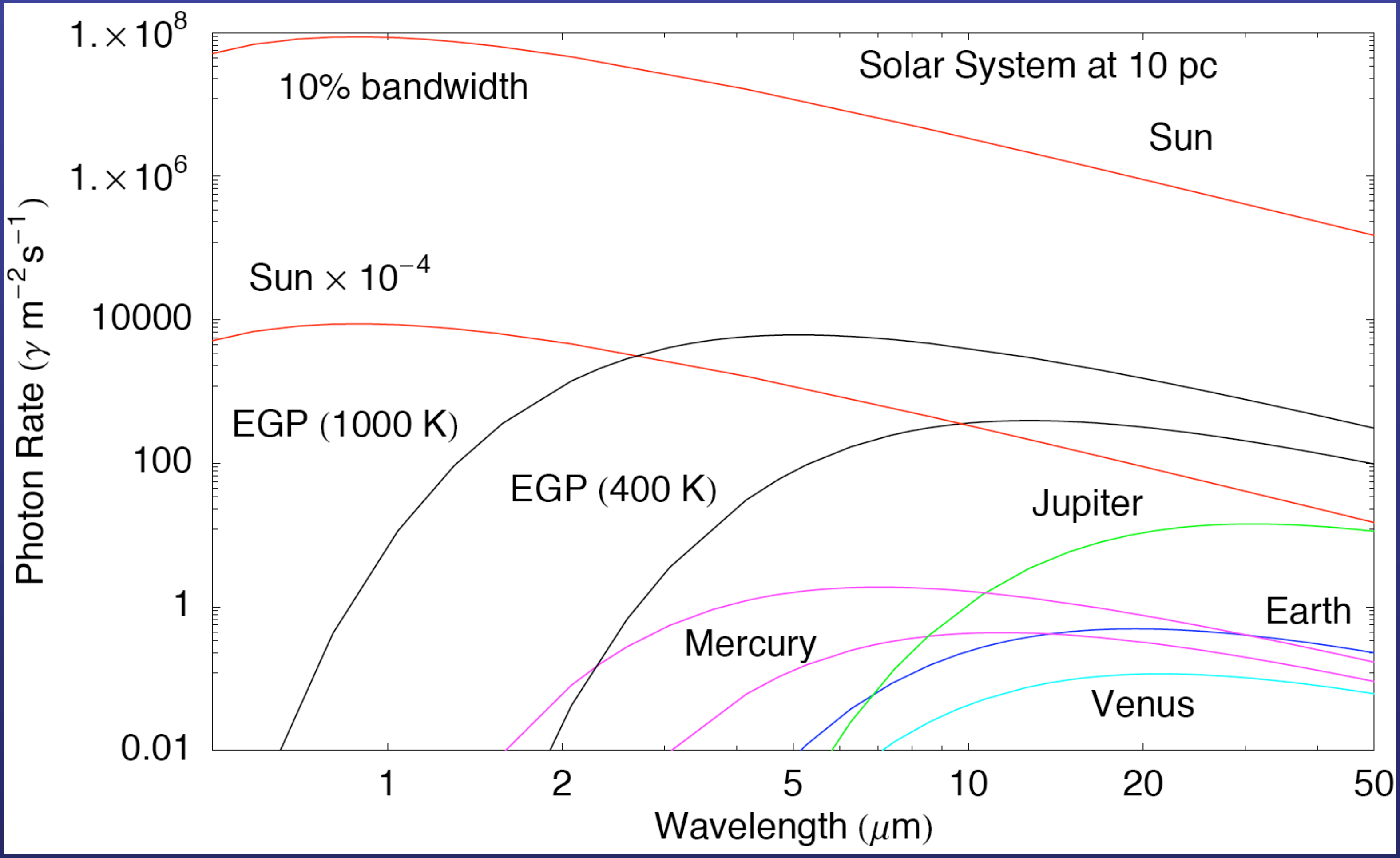
**The launch vehicle costs are provided by NASA Headquarters based on rates from the Kennedy Space Center. Future adjustments to this cost are unknown to the authors. The costs assume a small EELV with a 4 m fairing.

***Reserves are 30% on all budget categories, except for launch vehicle (0%), and EPO (10%). No reserves are required for Phase A.

Why High Sensitivity is Needed: Photometry of Our Planets and EGPs

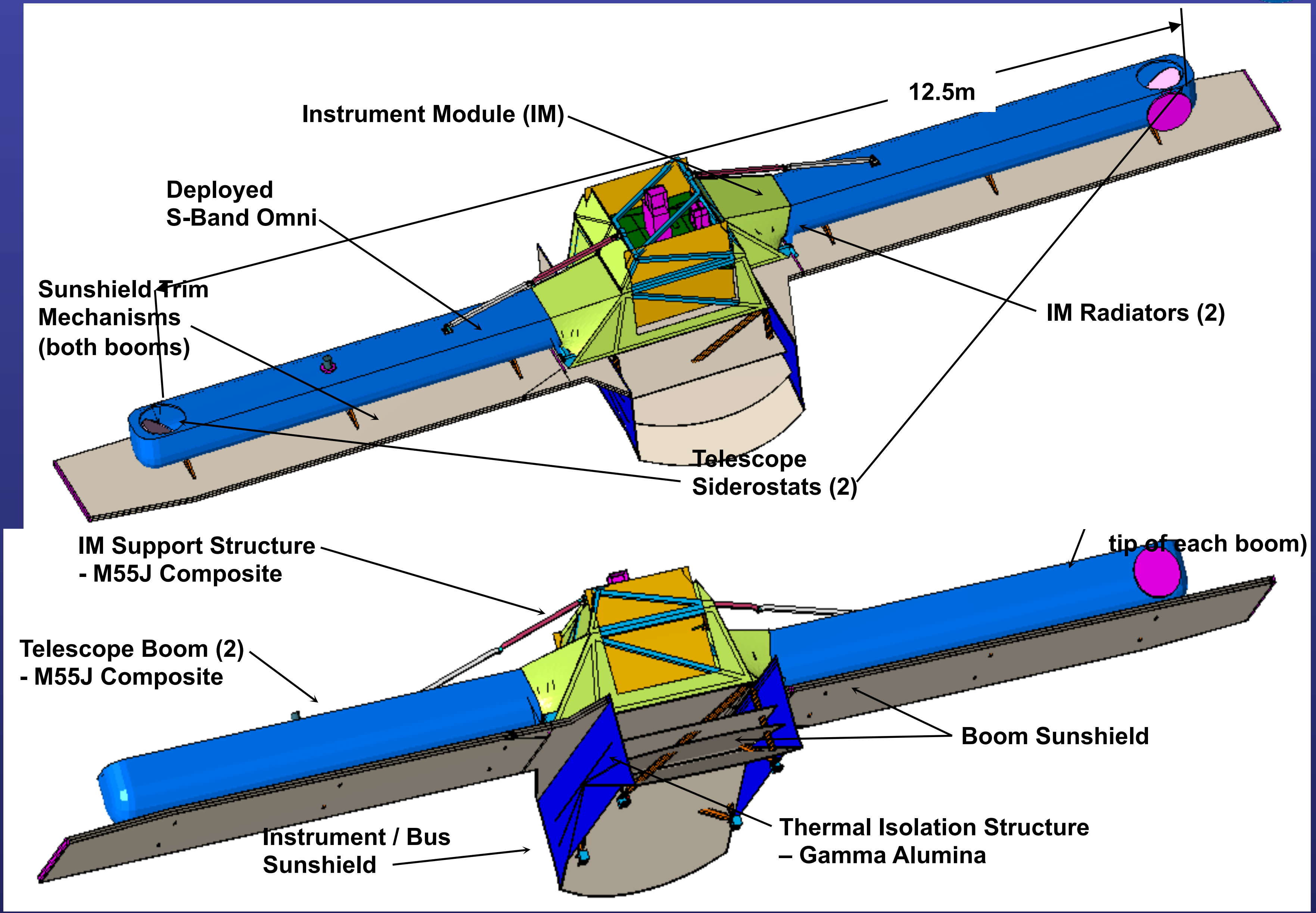


Photon Rates



Photon Rates are high enough that only modest apertures are needed!

Deployed FKSI C-Instrument



Some Refereed Papers of Interest

FKSI Specific:

- **"**Detection of Close-In Extrasolar Giant Planets with the Fourier-Kelvin Stellar Interferometer," W.C. Danchi, L.D. Deming, M. Kuchner, & S. Seager, *Astrophysical Journal Letters*, **597**, L57 (2003).
- "The Fourier-Kelvin Stellar Interferometer (FKSI) -- A practical infrared space interferometer on the path to the discovery and characterization of Earth-like planets around nearby stars," W. C. Danchi & B. Lopez, *Comptes rendus - Physique (C.R. Physique),* 8, 396-407 (2007).
- "Nulling interferometry: performance comparison between space and ground-based sites for exozodiacal disc detection," D. Defrere, O. Absil, V. Coude du Foresto, W.C. Danchi, R. den Hartog, *Astronomy and Astrophysics*, 490, 435-445 (2008).

Some Technologies:

Adaptive Nuller

- "Broadband phase and intensity compensation with a deformable mirror for an interferometric nuller," R. D. Peters, O. P. Lay, and M. Jeganathan, Appl. Opt. 47, 3920-3926 (2008)

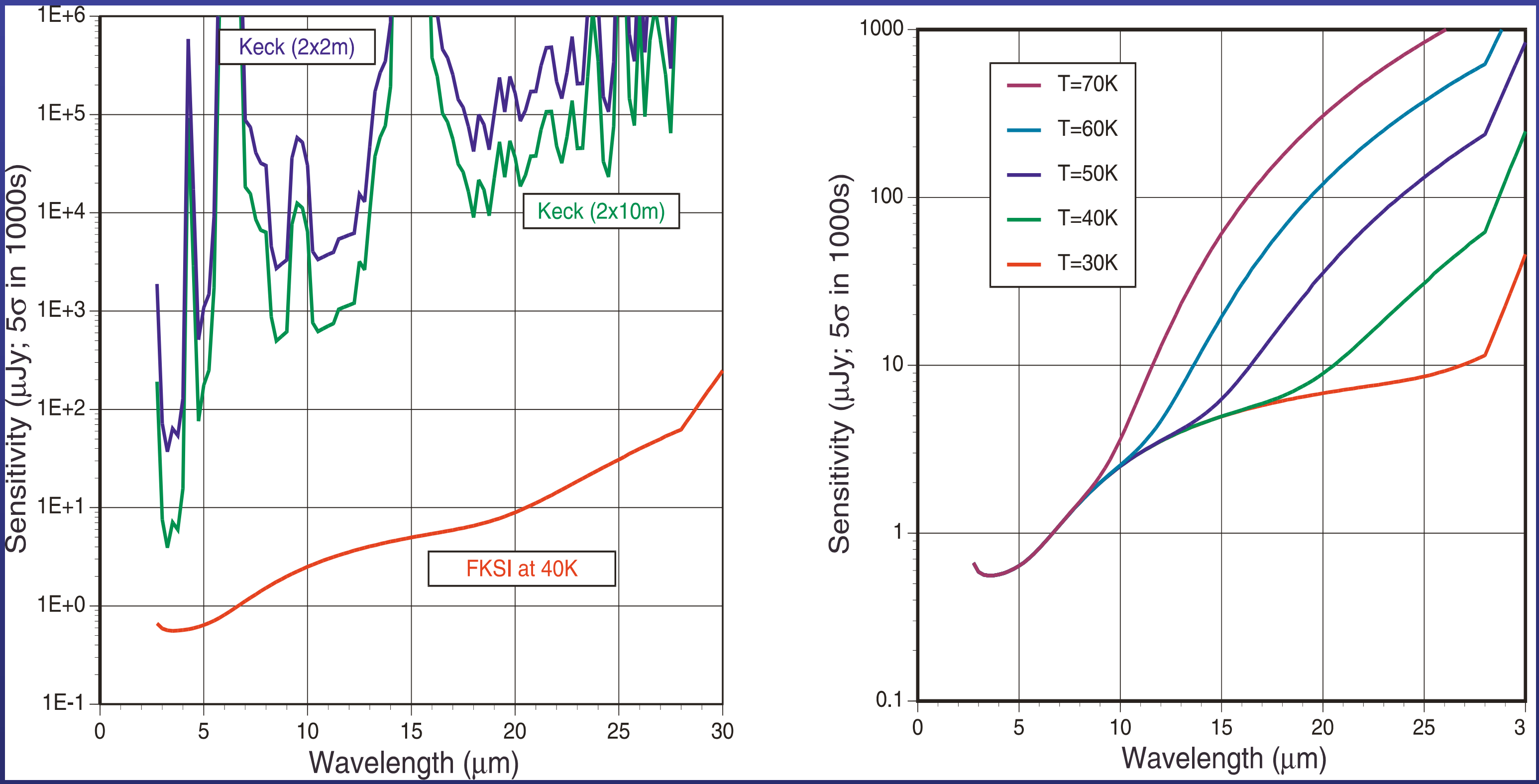
Spatial Filters

- "Modal filtering for midinfrared nulling interferometry using single mode silver halide fibers," A. Ksendzov, T. Lewi, O. P. Lay, S. R. Martin, R. O. Gappinger, P. R. Lawson, R. D. Peters, S. Shalem, A. Tsun, and A. Katzir, Appl. Opt. 47, 5728-5735 (2008)
- "Characterization of mid-infrared single mode fibers as modal filters," A. Ksendzov, O. Lay, S. Martin, J. S. Sanghera, L. E. Busse, W. H. Kim, P. C. Pureza, V. Q. Nguyen, and I. D. Aggarwal, Appl. Opt. 46, 7957-7962 (2007)

Achromatic Phase Shifters

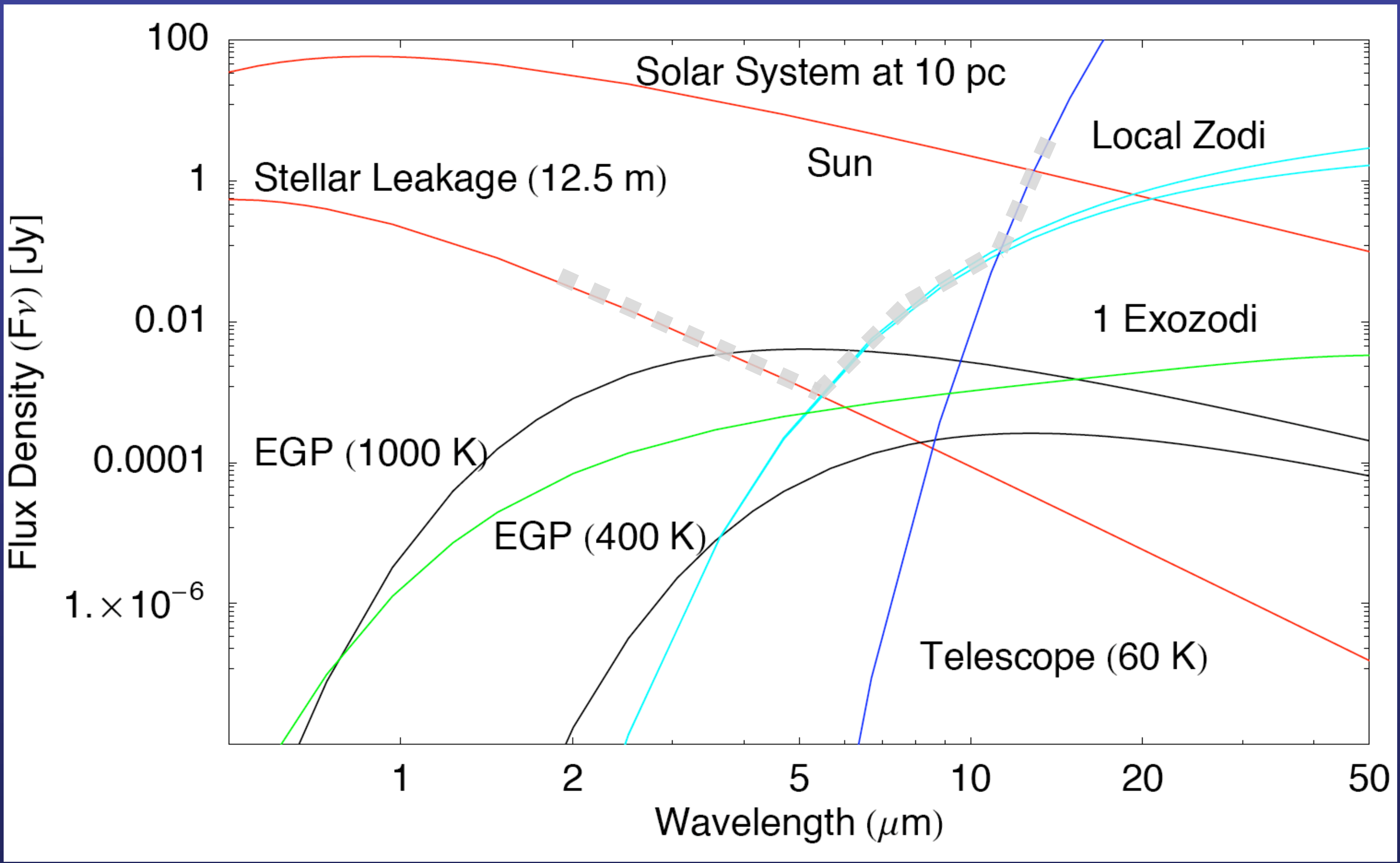
- "Experimental evaluation of achromatic phase shifters for mid-infrared starlight suppression," R. O. Gappinger, R. T. Diaz, A. Ksendvoz, P. R. Lawson, O. P. Lay, K. M. Liewer, F. M. Loya, S. R. Martin, E. Serabyn, and J K. Wallace, Appl. Opt. 48, in press (2009)

A SMALL Cooled Space Telescope is Very Sensitive Compared to a LARGE Ground-based Telescope

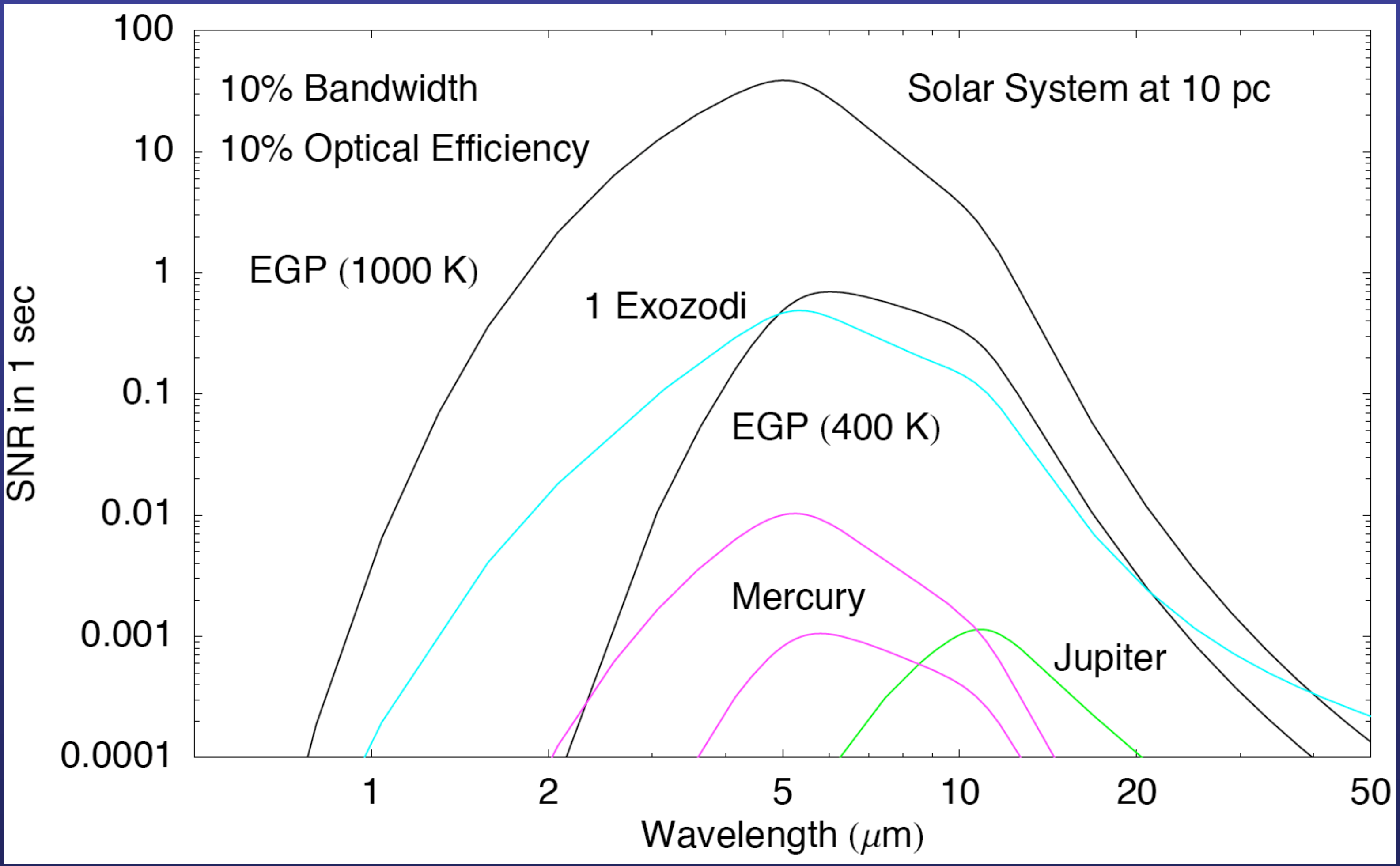


Left panel . The sensitivity of the FKSI system (1 m telescopes) with telescope temperature at 40 K compared to either two 10 m Keck telescopes or two Keck 2 m outrigger telescopes.
Right panel. Effect of telescope temperature on FKSI sensitivity.

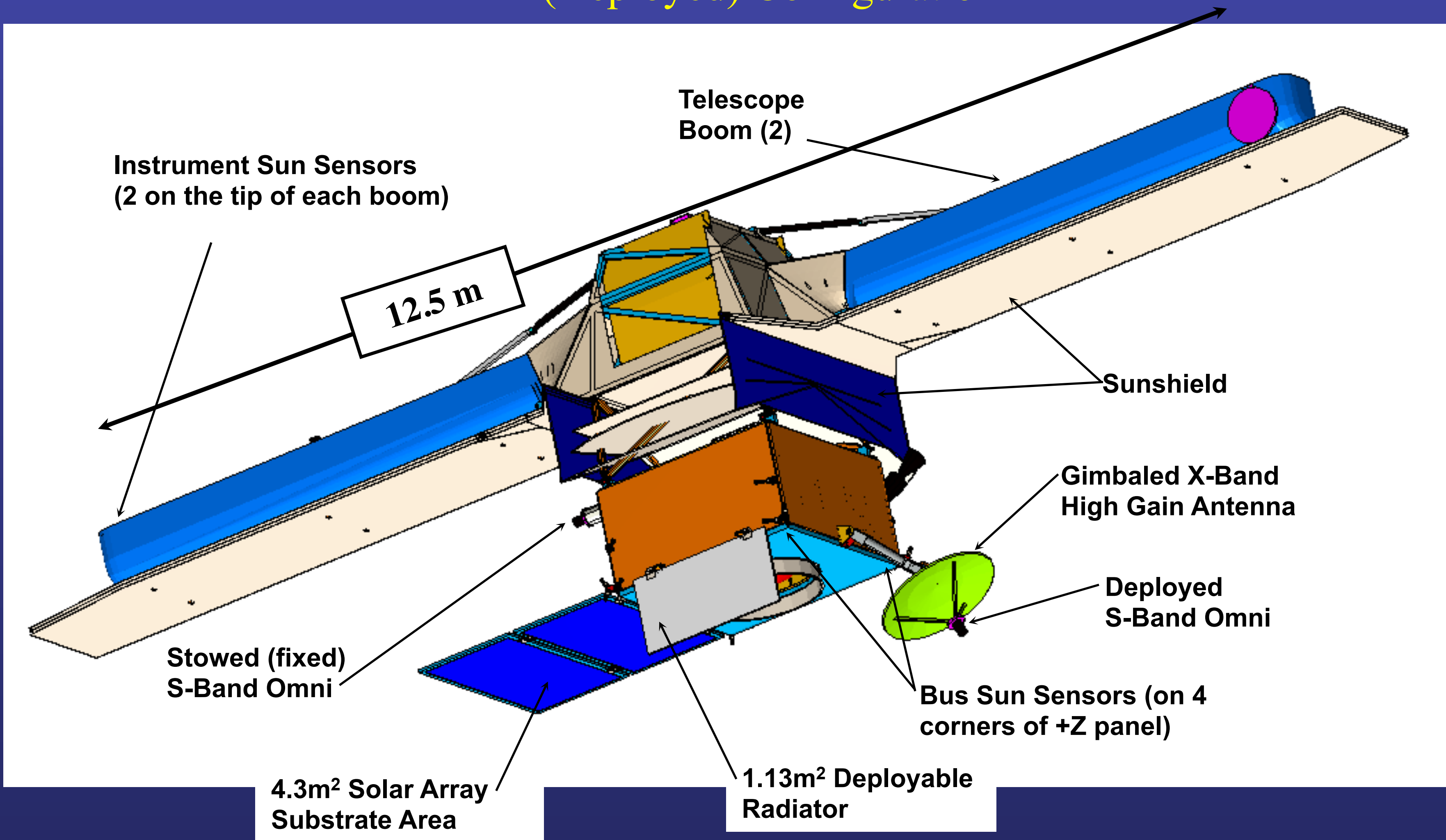
Noise and Signal Source Flux Densities



Signal-to-Noise in 1 s for 1 m^2 collecting area



FKSI Observatory in Operational (Deployed) Configuration



FKSI Requirements Flowdown

Science Goals

- Characterize Extrasolar Giant Planet Atmsopheres
- Measure resonant disk structures in exo-zodiacal debris disks to find and characterize extrasolar planets
- Understand evolution of young stellar systems and their planet forming potential
- Measure detailed structures inside active galactic nuclei

→

Measurement Capabilities

Near-IR and Mid-IR Imaging and Spectroscopy

Spectral Range

~3-8 μm

Angular Resolution

~ 41 (λ/5) mas

Spectra Resolving Power

λ/Δλ ~ 25

Field of View

~ 1-2 arcsec

Sensitivity

< 2 μJy continuum

Observations

At least one target field per day

→

Engineering Implications

Optical System and Metrology

•2 light collectors plus nulling beam combiner and spectrometer

•Baseline ~12 m

•~0.5-1 m diameter collector mirrors

•65 K optics
~ λ/10 rms at 632 nm

•Delay line metrology
~ 3 nm

•~15 nm rms pathlength control requirement

•Sub-arcsecond relative pointing

Detectors

< 10 e-/s dark current
< 10e- read noise
~128^2 pixels

Orientation

•Able to view >+/- 20° from ecliptic

→

Key Technologies

Detectors

•Very low dark current

•Very low read noise

•~35 K operating temperature desired

Active and Passive Cooling

•Efficient high-capacity cryocoolers

•~30 K cryocoolers

•Deployable mult-layer sunshades

Structures and mechanisms

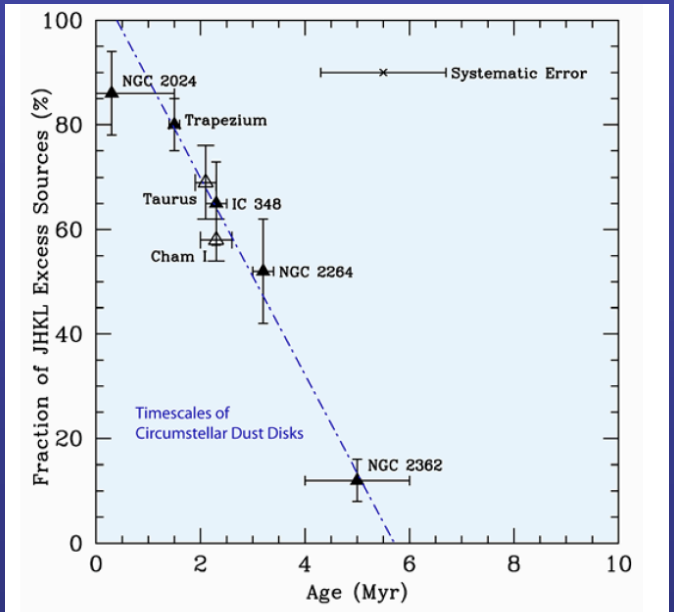
•Deployable truss with light collectors

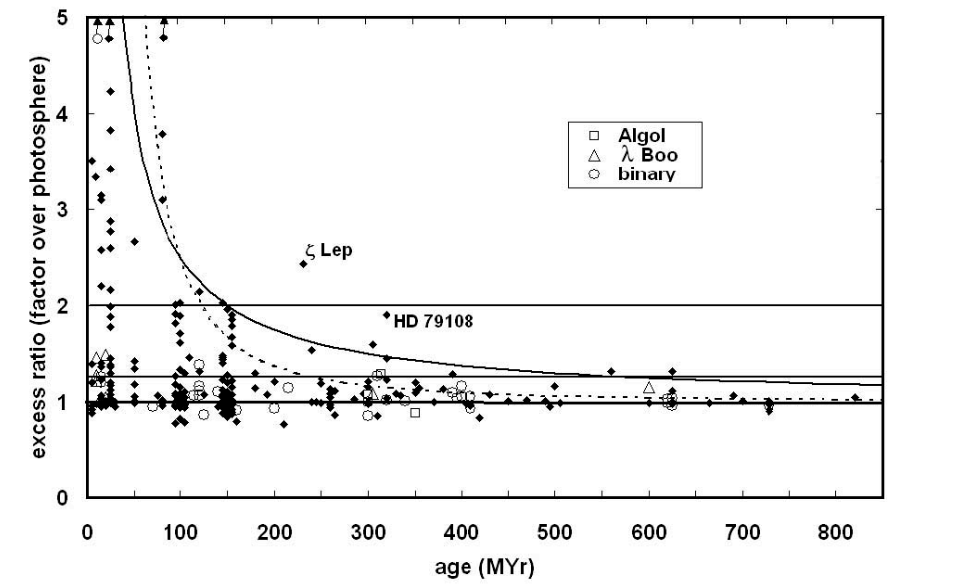
Interferometry

•Cryogenic high precision delay line

•Cryogenic optical fibers for beam cleanup

Evolution of Debris Disks

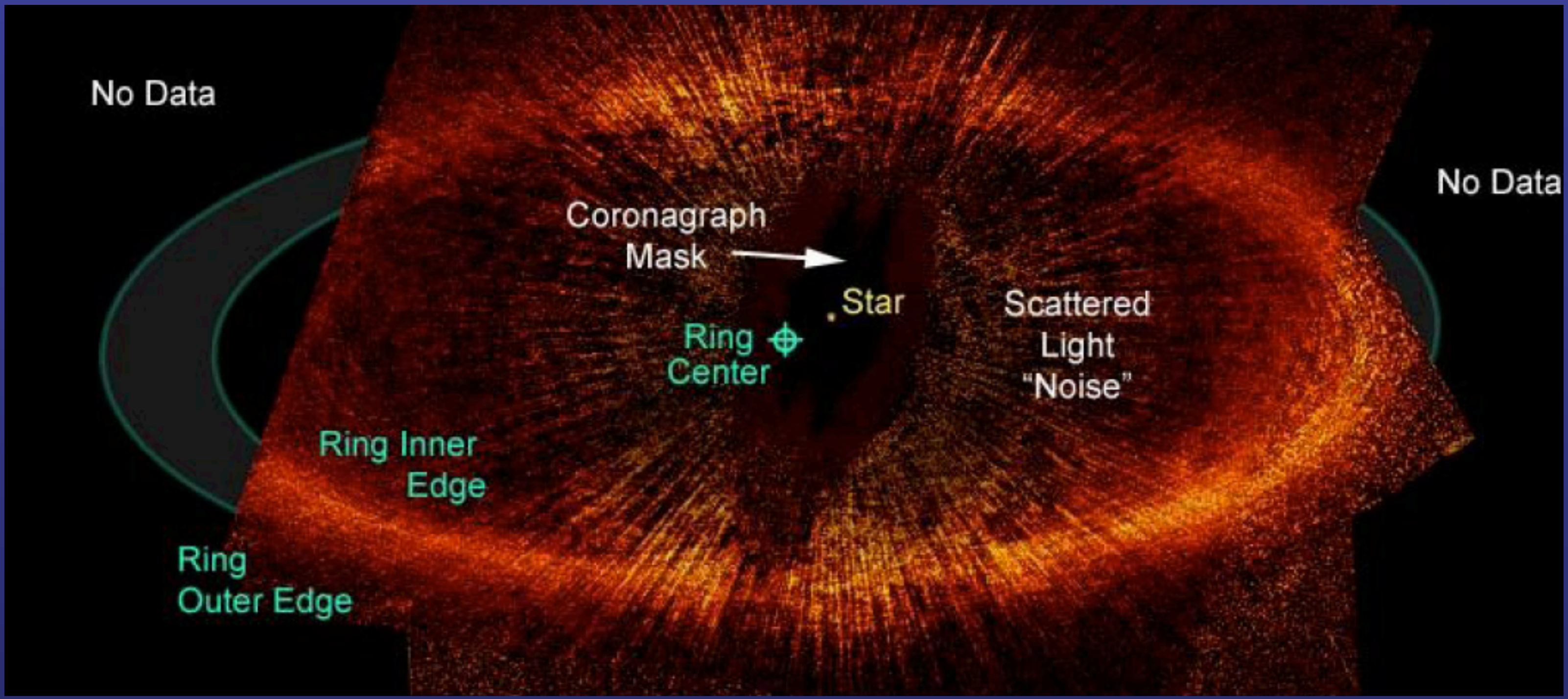




Originally from IRAS, now detailed studies from Spitzer on A stars (Rieke et al. 2005) and F,G,K stars (Beichman, Bryden, Kim et al. 2005)

Many interesting examples worth studying in more detail.

Structure of Debris Disks
Fomalhaut -- HST



HST image of Fomalhaut from Graham and Clampin (2005). Note ring is not centered on the star!

Ground-based interferometry

Keck Interferometer

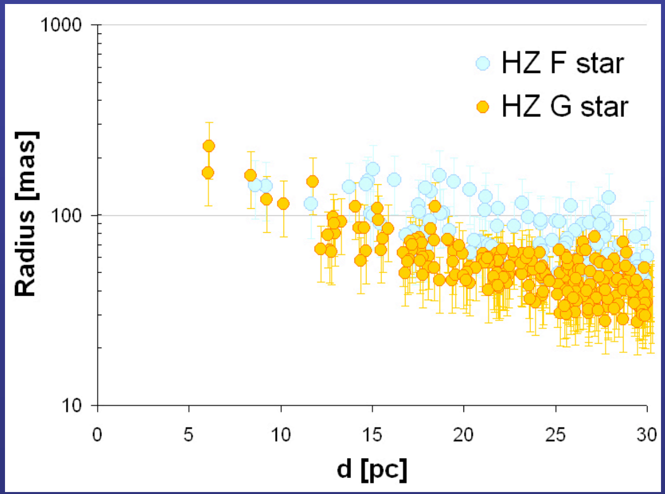
- Protoplanetary disk studies (T Tauri & Herbig Ae/Be stars)
- Debris Disks Around Nearby Stars (Key Science Projects) with limits around 100-200 Solar System Zodis

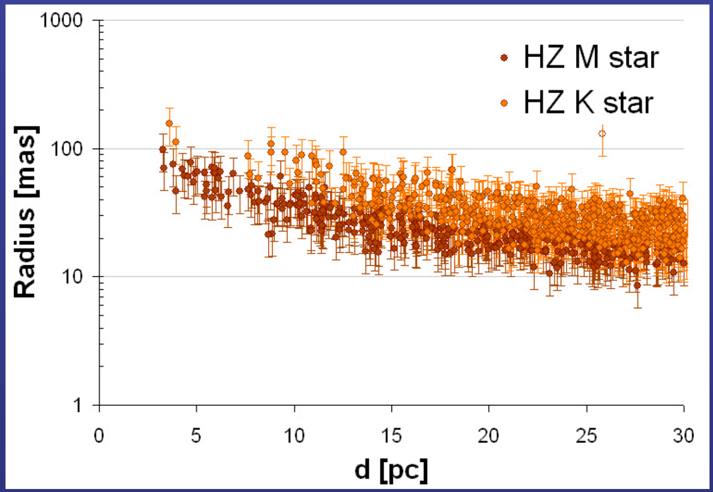
Large Binocular Telescope Interferometer

- Debris Disks with lower limits ~30 Solar System Zodis

These projects have been essential to the development of the nulling technique and they will produce important near-term results.

Angular Size of the Habitable Zone





Size of habitable zone is 10 < HZ (mas) < 200

for all F,G,K, M stars < 30 pc from Earth

Interferometer Resolution

Interferometer Resolution is:

$\lambda/(2B)$ where λ is wavelength and B is the baseline.

For 100 mas resolution --> B = 10 m at 10 μm

10 mas resolution --> B = 100 m at 10 μm

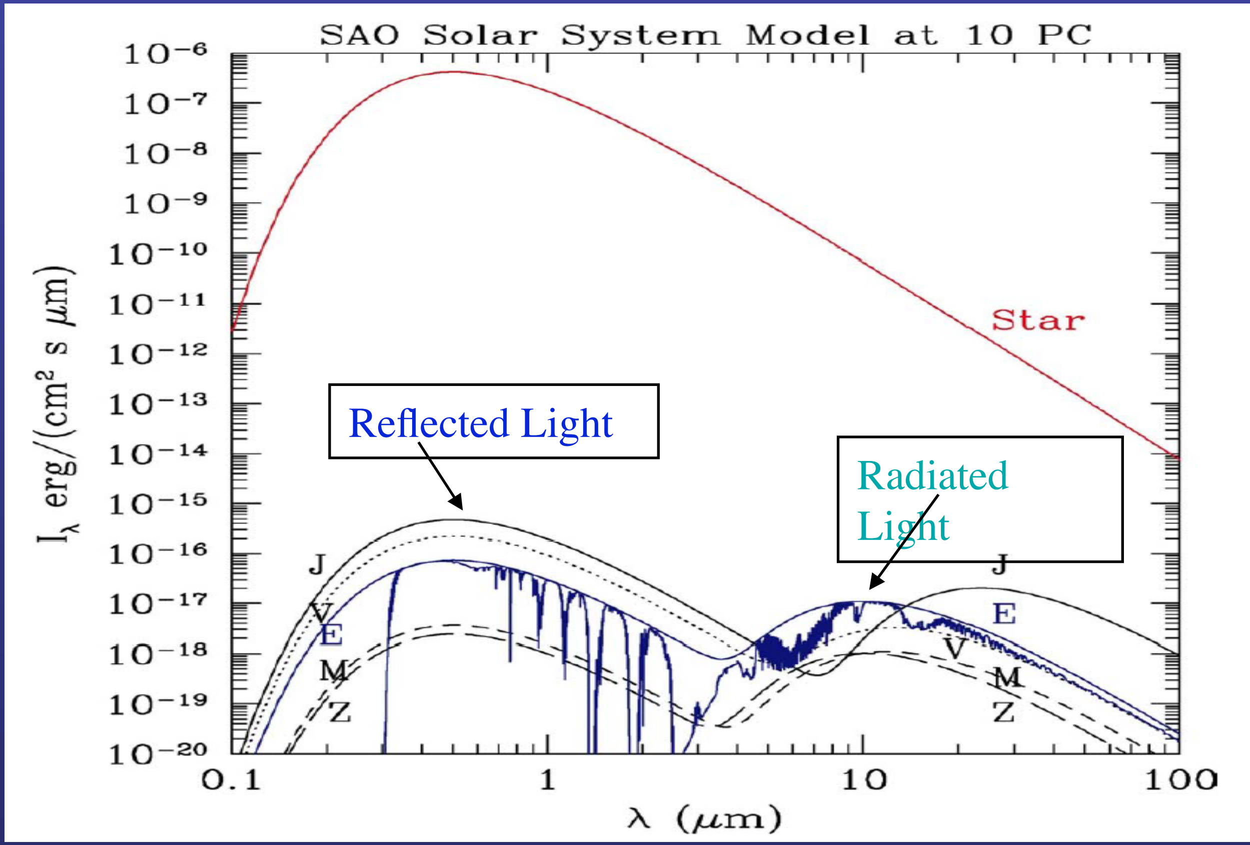
***This sets the minimum baseline size*.**

A 20-40 m baseline at 10 μm is adequate resolution for a substantial number of nearby F,G,K, stars, or 1/2 that if the center wavelength is 5 μm.

The Solar System Viewed from 10 pc

You can search for planets directly either from *reflected* starlight or *re-radiated* starlight

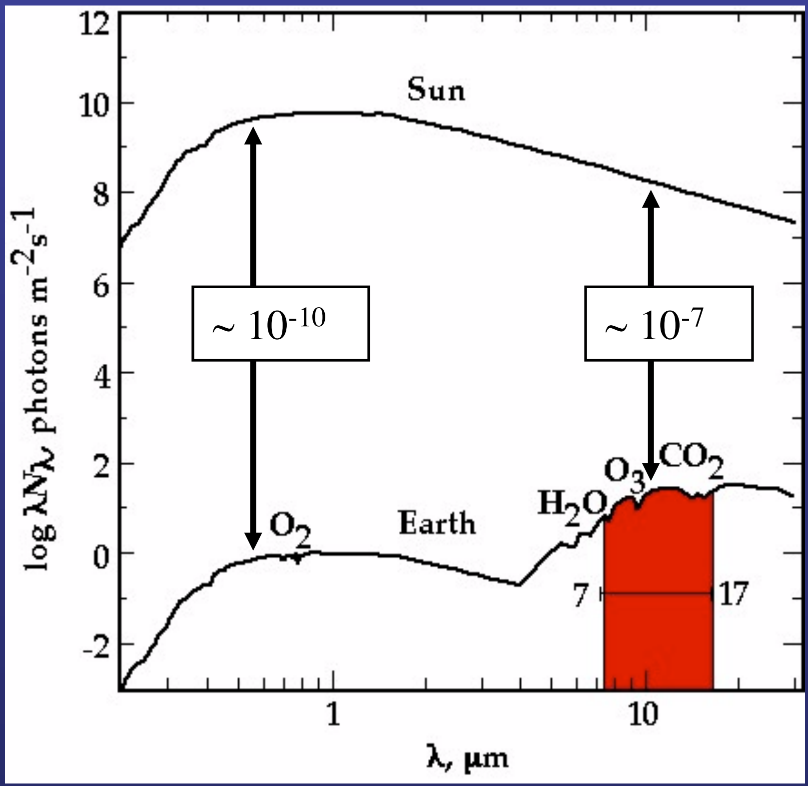
Notice that *different planets* have *different spectra* in the infrared



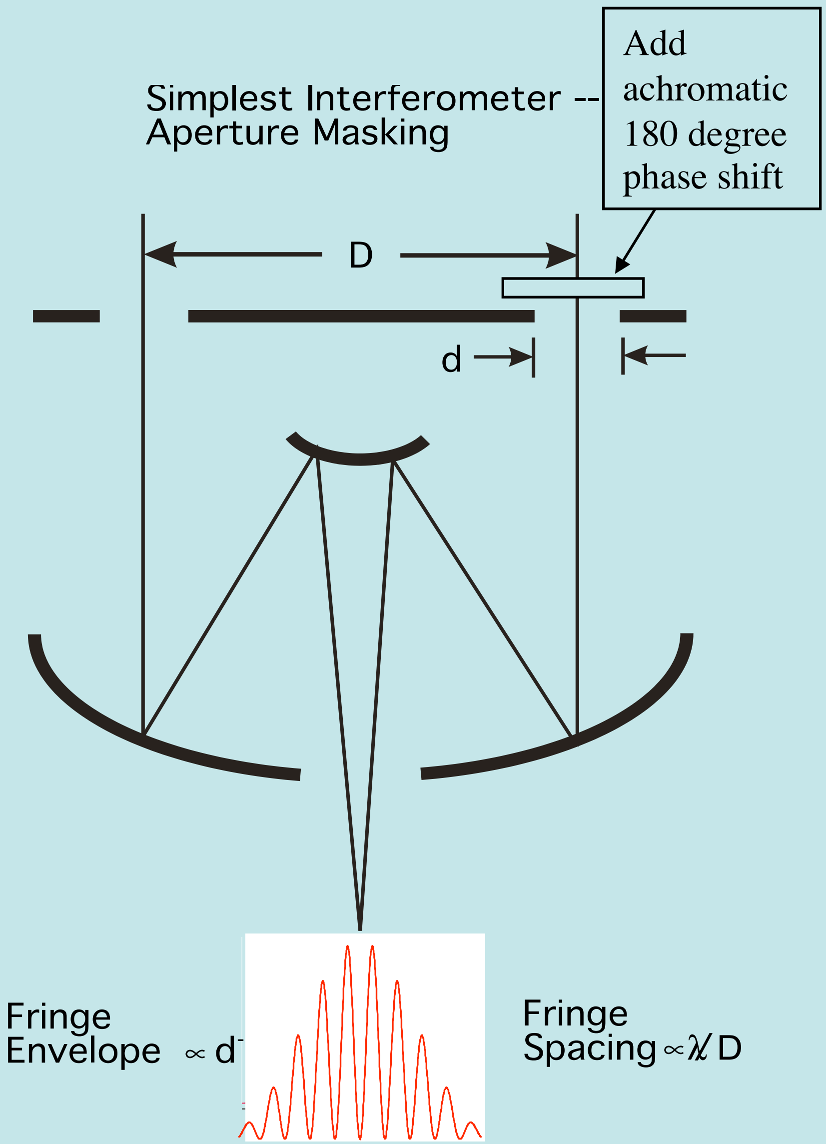
DesMarais et al. (2002)

Detecting Earth-size Planets is Difficult

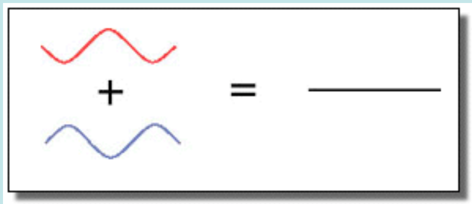
- Detecting light from planets beyond solar system is hard:
  - Earth sized planet emits few photons/sec/m^2 at 10 μm
  - Parent star emits 10^6 more
  - Planet within 1 AU of star
  - Exozodi dust emission in target solar system ~300 brighter than planet



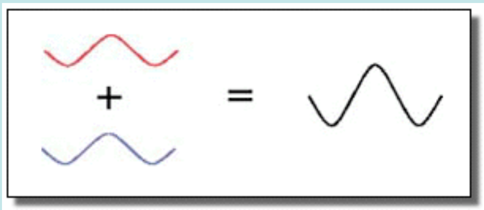
A simple nulling interferometer



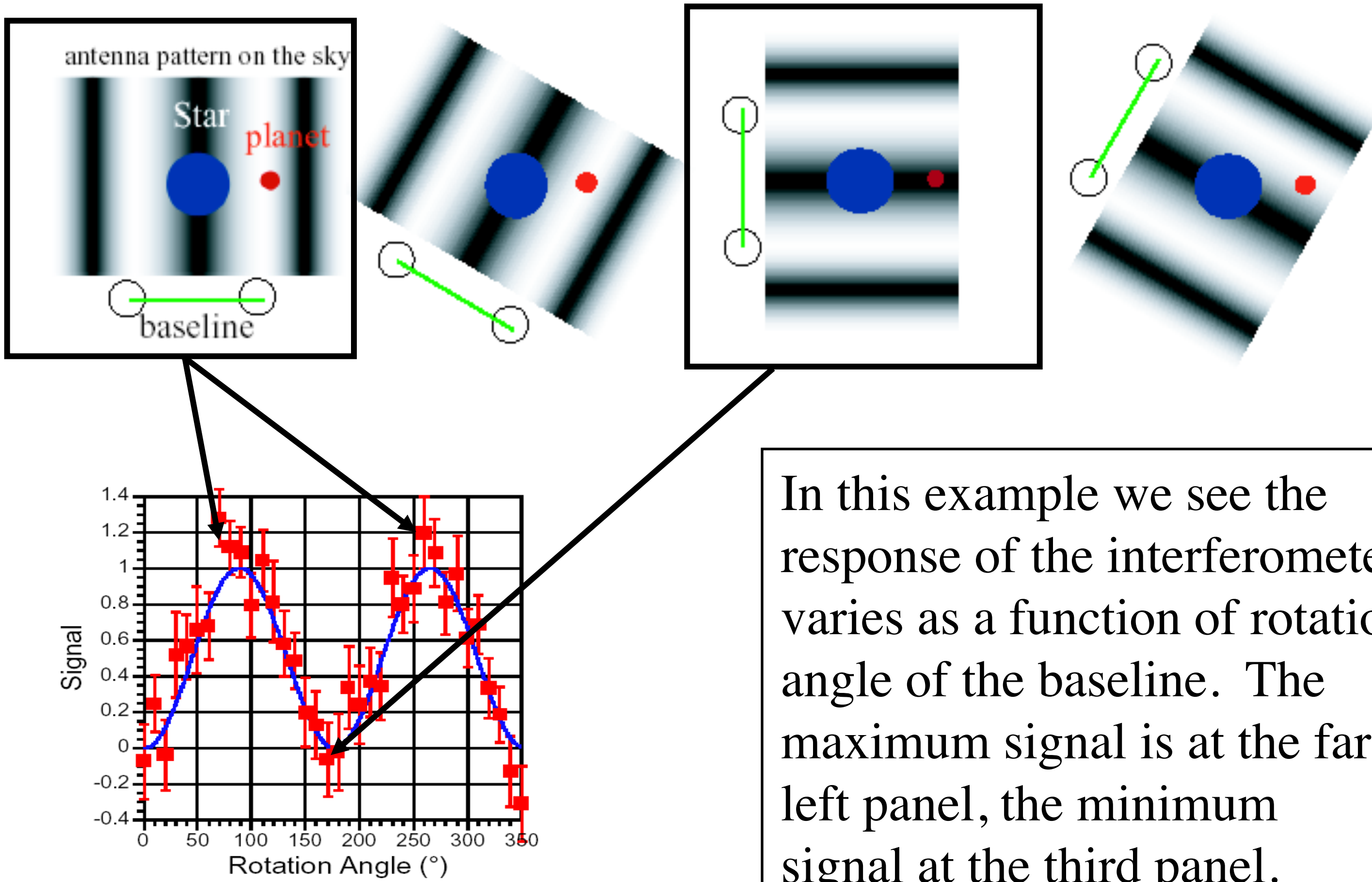
•You get a null when pathlengths are equal on both sides -- "white light null fringe"



•You get a peak when pathlengths differ by one half wavelength -- a "bright fringe"



A Simple Example of an Interferometric Detection of a Planet



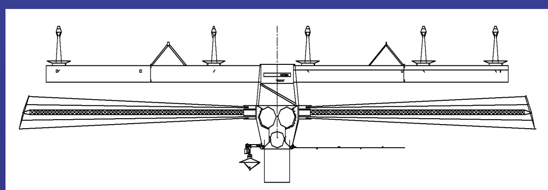
In this example we see the response of the interferometer varies as a function of rotation angle of the baseline. The maximum signal is at the far left panel, the minimum signal at the third panel.

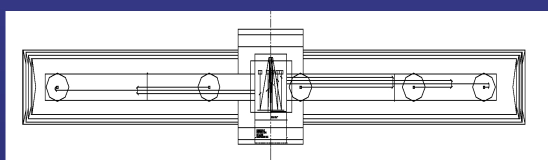
FKSI Mission Design Evolution

- GSFC actively developed FKSI mission designs since fall of 2001 with an intensive effort in 2002-2003
  - Had targeted Discovery AO
- Mission design moved through A, B, and C iterations as costs were evaluated and as FKSI PI and Science Team refined science goals
  - "A" Design focused on a broad mission including general infrared astrophysical imaging at high angular resolution (20 m baseline), nulling, and low resolution spectroscopy (5 -- 1 m telescopes, 5-28 micron wavelength region)
  - "B" Design focused on a minimal version of the A system (3 – 1 m telescopes, 5-28 micron region, minimal sunshade)
  - "C" Design focused on nulling in 3-8 micron region (could be up to 10 or 12 microns, depending on detectors), and low resolution spectroscopy (2 -- 0.5 m telescopes, moderate sunshade)

FKSI Mission Trade Space Explored

“A” Design



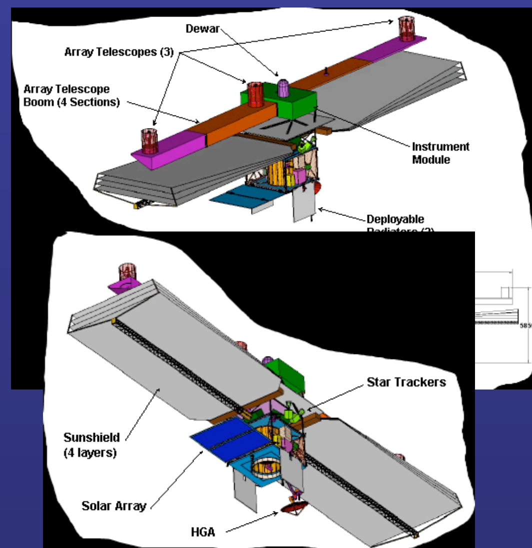


No. of Telescopes: 5
Max. Baseline: 20 m (4-fold boom)
Sci. Spectral Range: 5 - 28 microns
Interferometer Type: Fizeau (image plane)
Instrument Elements: Angle Tracker
Fringe Tracker
Imaging FTS
Nuller

Implementation: Two 6K adv. tech. mech. coolers, four 40K mech. coolers, sun shade separate from instrument, requires 5m LV fairing

Cost: $$$

“B” Design

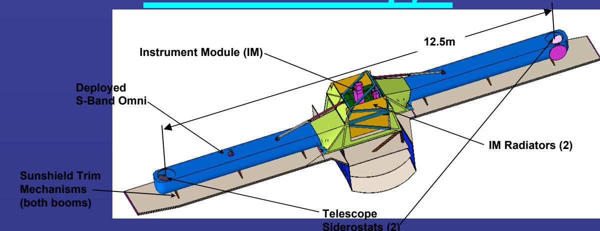


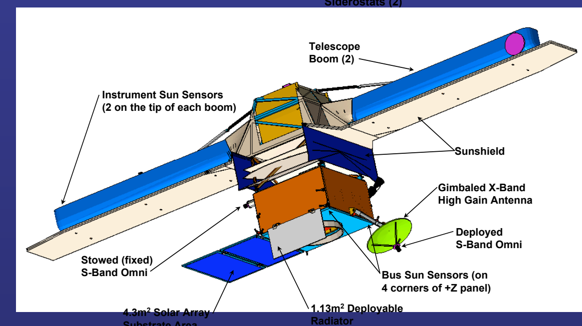
No. of Telescopes: 3
Max. Baseline: 16 m (4-fold boom)
Sci. Spectral Range: 5 - 28 microns
Interferometer Type: Fizeau (image plane)
Instrument Elements: Angle Tracker
Fringe Tracker
Imaging FTS
(R=10,000)
Nuller

Implementation: 6K solid H2 cryostat + two 30K mech. coolers, sun shade separate from instrument, requires 5m LV fairing

Cost: $$

“C” Design



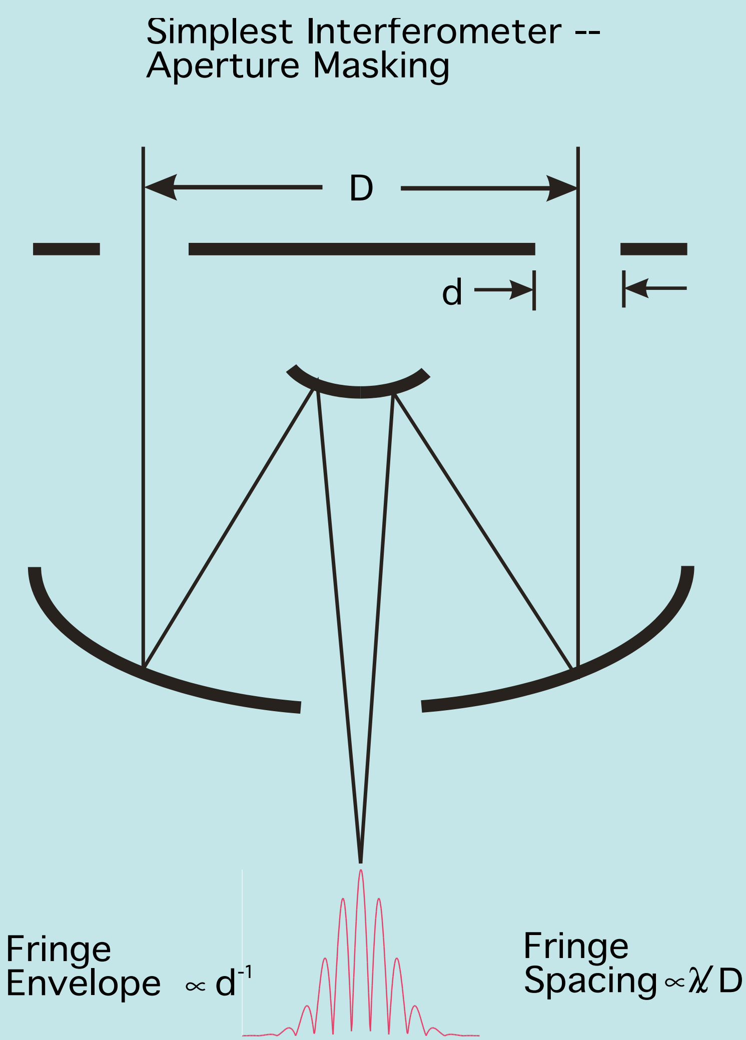


No. of Telescopes: 2 (siderostat)
Max. Baseline: 12.5 m (2-fold boom)
Sci. Spectral Range: 3 - 8 microns
Interferometer Type: Michelson (pupil plane)
Instrument Elements: Angle Tracker
Fringe Tracker
Nuller w/ R=20

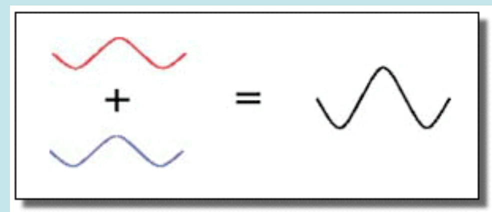
Implementation: One 32K mech. cooler, sun shade tied to instrument, fits in 4m LV fairing

Cost: $

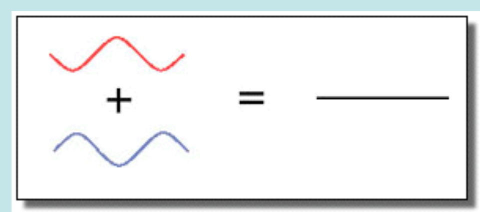
A simple interferometer



•You get a peak when pathlengths are equal on both sides -- "white light fringe"

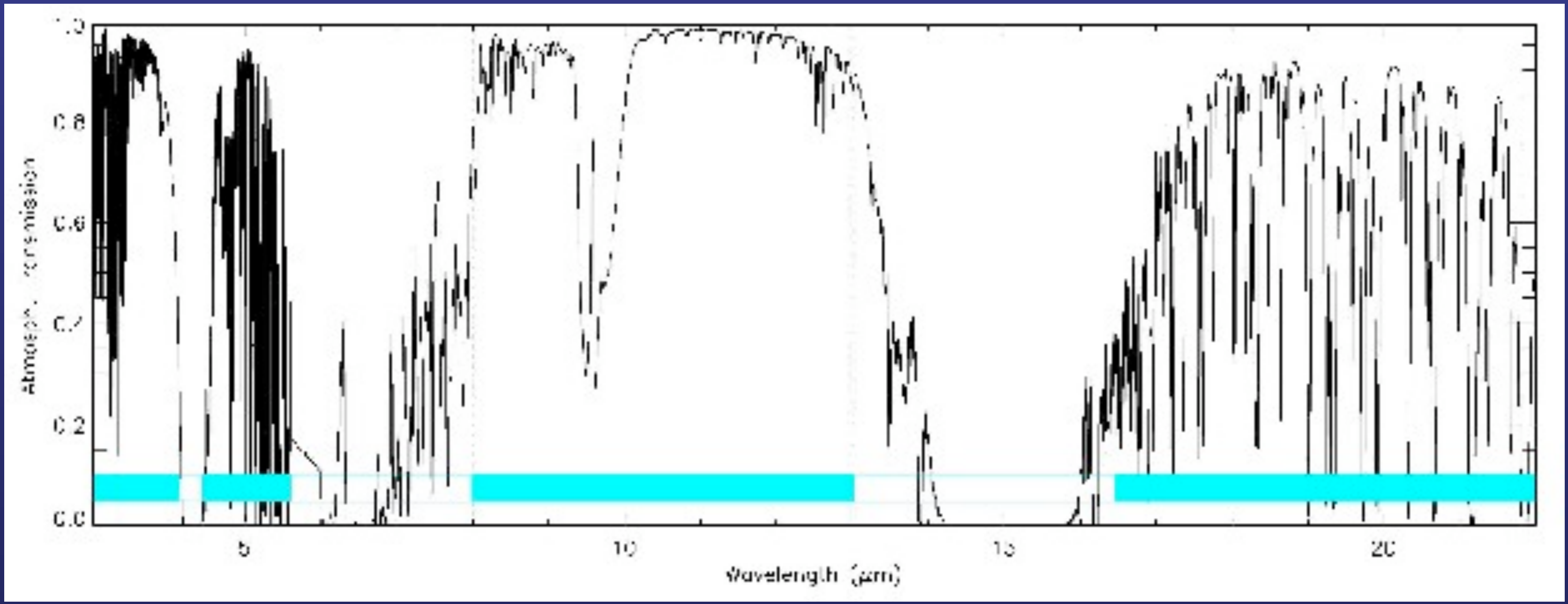


•You get a null when pathlengths differ by one half a wavelength -- a "dark fringe"

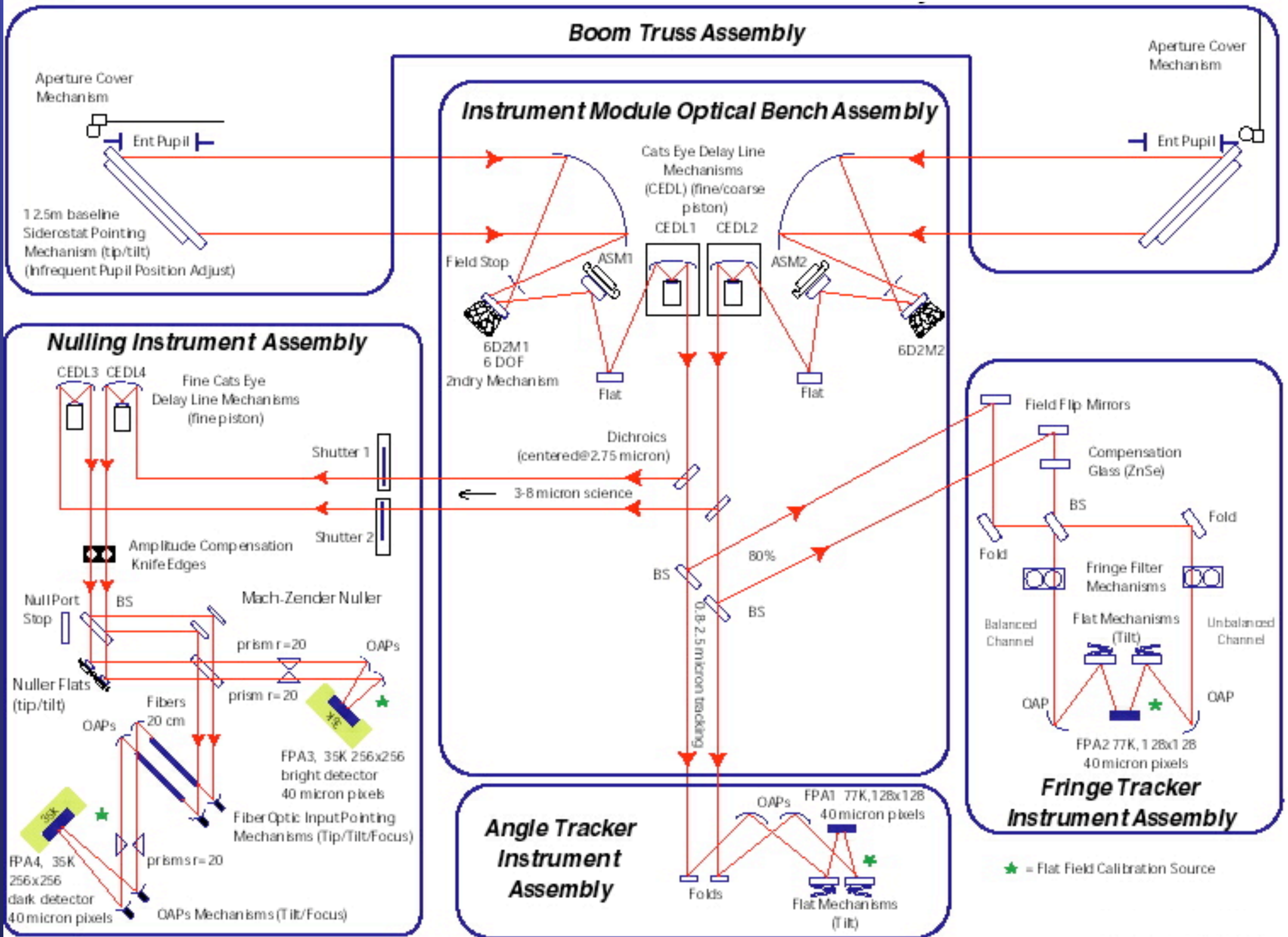


Why IR from Space?

Atmospheric transmission is a problem



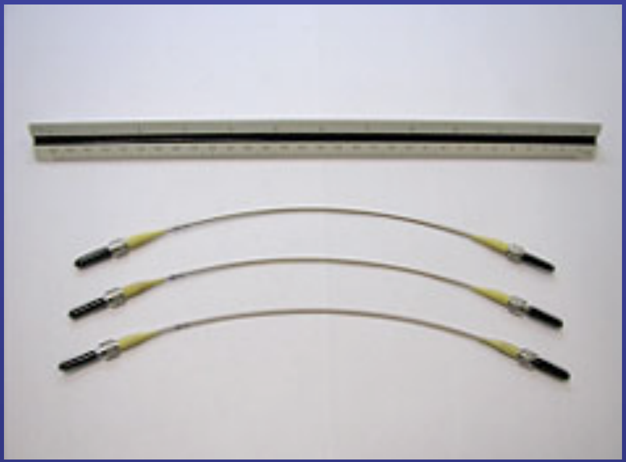
FKSI Instrument Module and Boom Subsystem



Key Technologies

Single-Mode Mid-Infrared Fibers

- **Chalcogenide Fibers** (NRL)
  - A. Ksendzov et al., "Characterization of mid-infrared single mode fibers as modal filters," Applied Optics 46, 7957-7962 (2007)
  - Transmission losses 8 dB/m
  - Suppression of 1000 for higher order modes
  - Useable to ~11 microns

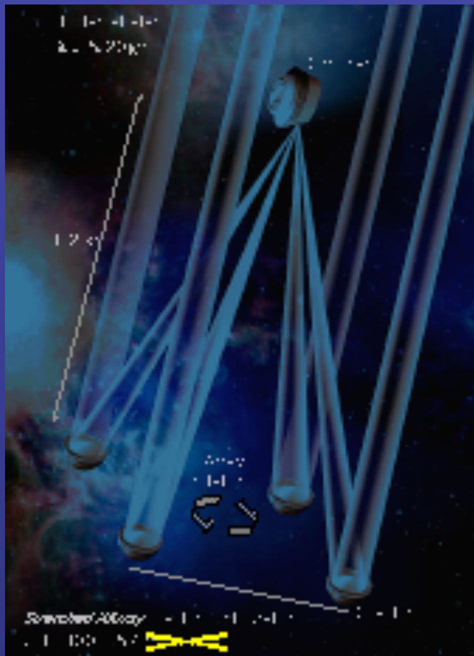


Example Chalcogenide Fibres, produced on contract by the Naval Research Laboratory

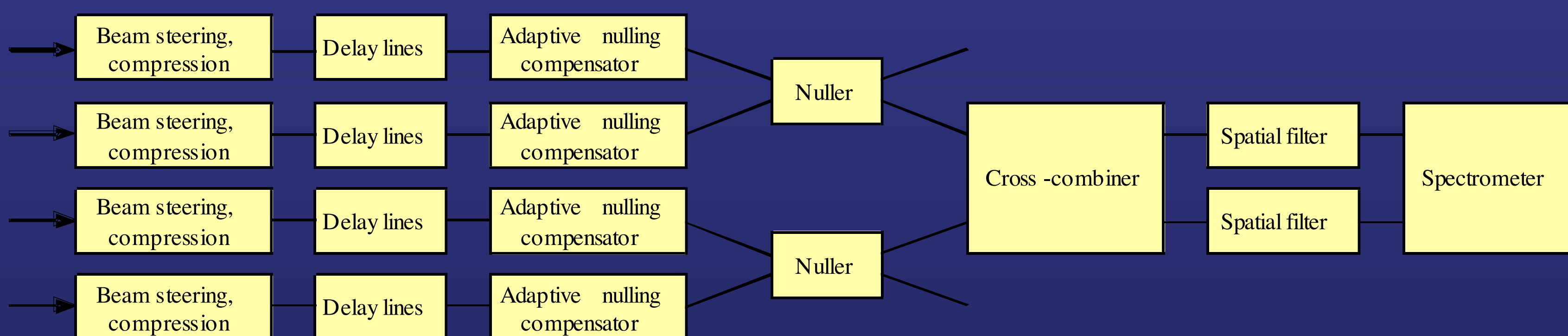
- **Silver-Halide Fibers** (Tel Aviv Univ)
  - A. Ksendzov et al. "Model filtering in mid-infrared using single-mode silver halide fibers," Applied Optics, submitted.
  - Transmission losses 12 dB/m
  - Suppression of 16000 possible with a 10-20 cm fibre, with aperturing the output.
  - Useable to ~18 microns (?)

http://planetquest.jpl.nasa.gov/TPF-I/spatialFilters.cfm

TPF Architecture

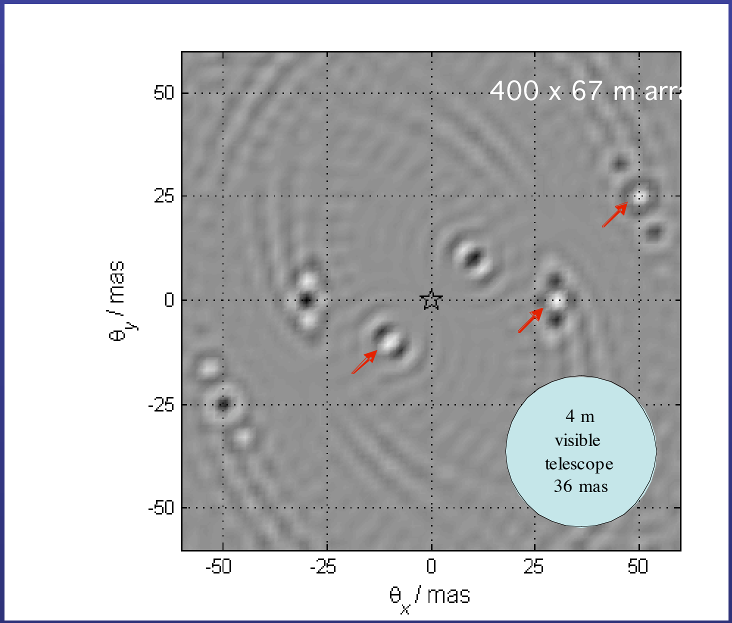


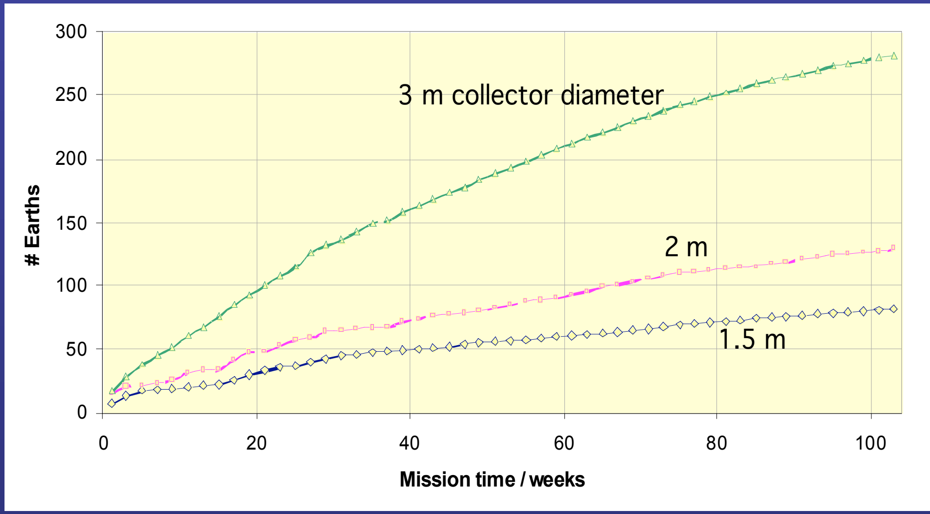
Emma X-Array Architecture resulted from detailed studies of the past several years



Schematic of beam combiner optics

TPF Performance Summary





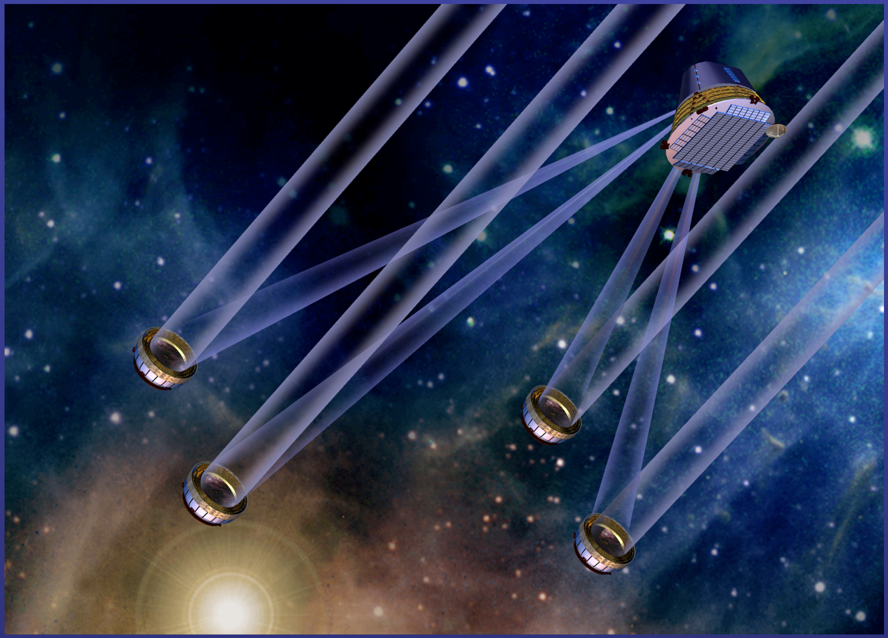
Simulated ‘dirty’ image from Emma X-Array, prior to deconvolution. Angular resolution is 2.5 mas. Planet locations are indicated by red arrows.

Predicted number of Earths detectable by Emma X-Array architecture as a function of elapsed mission time and collector diameter

Terrestrial Planet Finder Interferometer

Salient Features

- Formation Flying Mid-IR nulling Interferometer
- Starlight suppression to and 10^{-5} (mid-IR)
- Heavy launch vehicles
- L2 baseline orbit
- 5 year mission life (10 year goal)
- Potential collaboration with European Space Agency



Science Goals

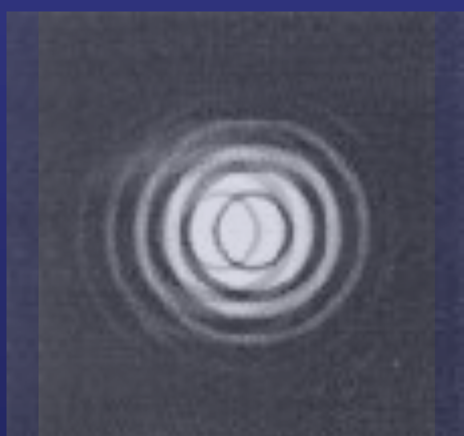
- Detect as many as possible Earth-like planets in the "habitable zone" of nearby stars via their reflected light or thermal emission
- Characterize physical properties of detected Earth-like planets (size, orbital parameters, albedo, presence of atmosphere) and make low resolution spectral observations looking for evidence of a *habitable* planet and bio-markers such as O_2, O_3, CO_2, CH_4 and H_2O
- Detect and characterize the components of nearby planetary systems including disks, terrestrial planets, giant planets and multiple planet systems
- Perform general astrophysics investigations as capability and time permit

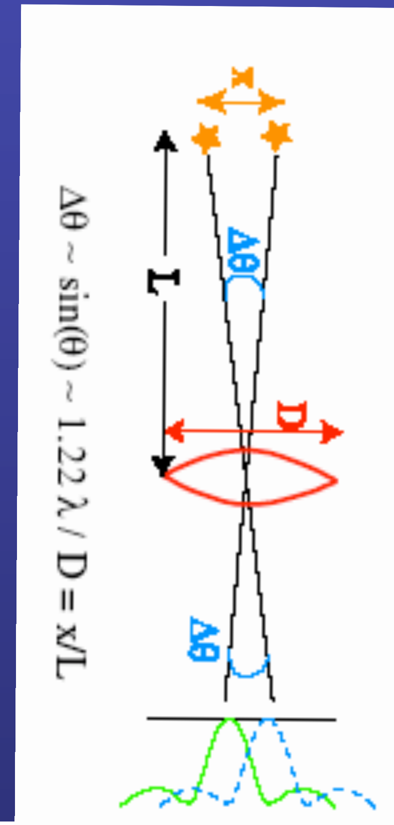
Resolution of a conventional telescope:
Rayleigh Criterion

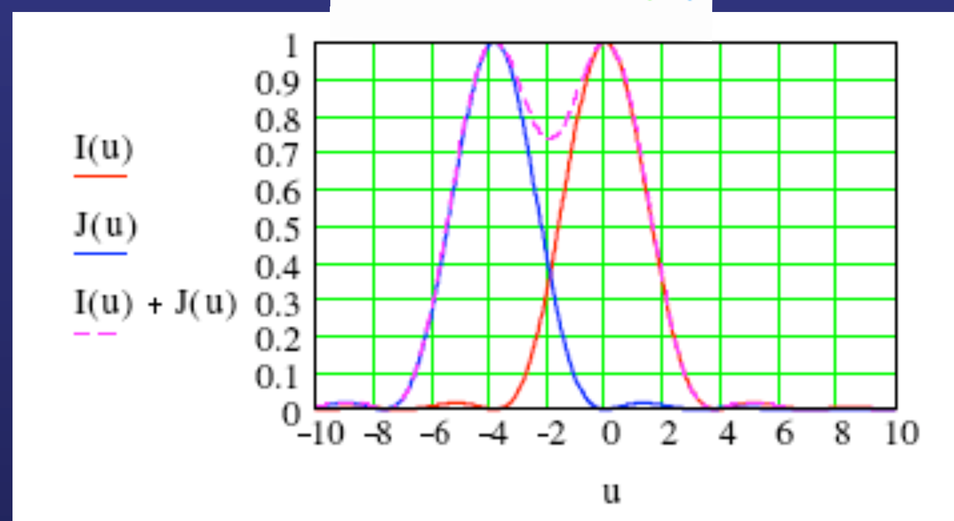
$\Delta\theta \sim 1.22\,\lambda / D$

λ = wavelength of light

D = telescope diameter



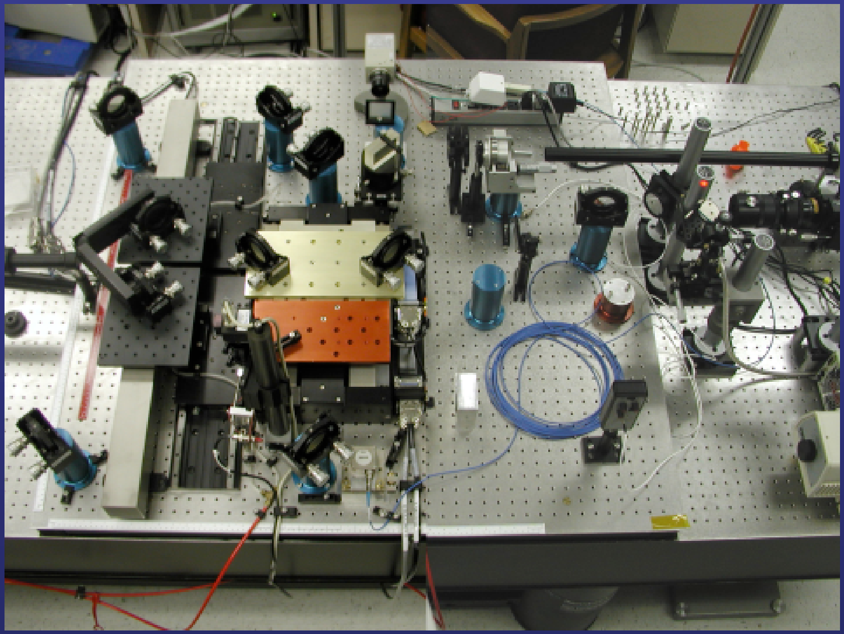


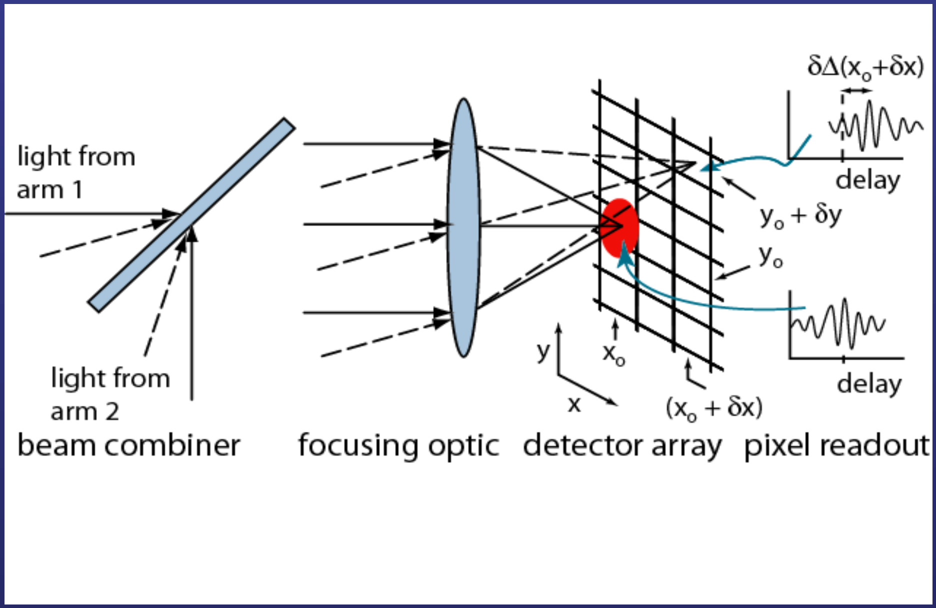


Wide-Field "Double Fourier" Interferometry in the Lab

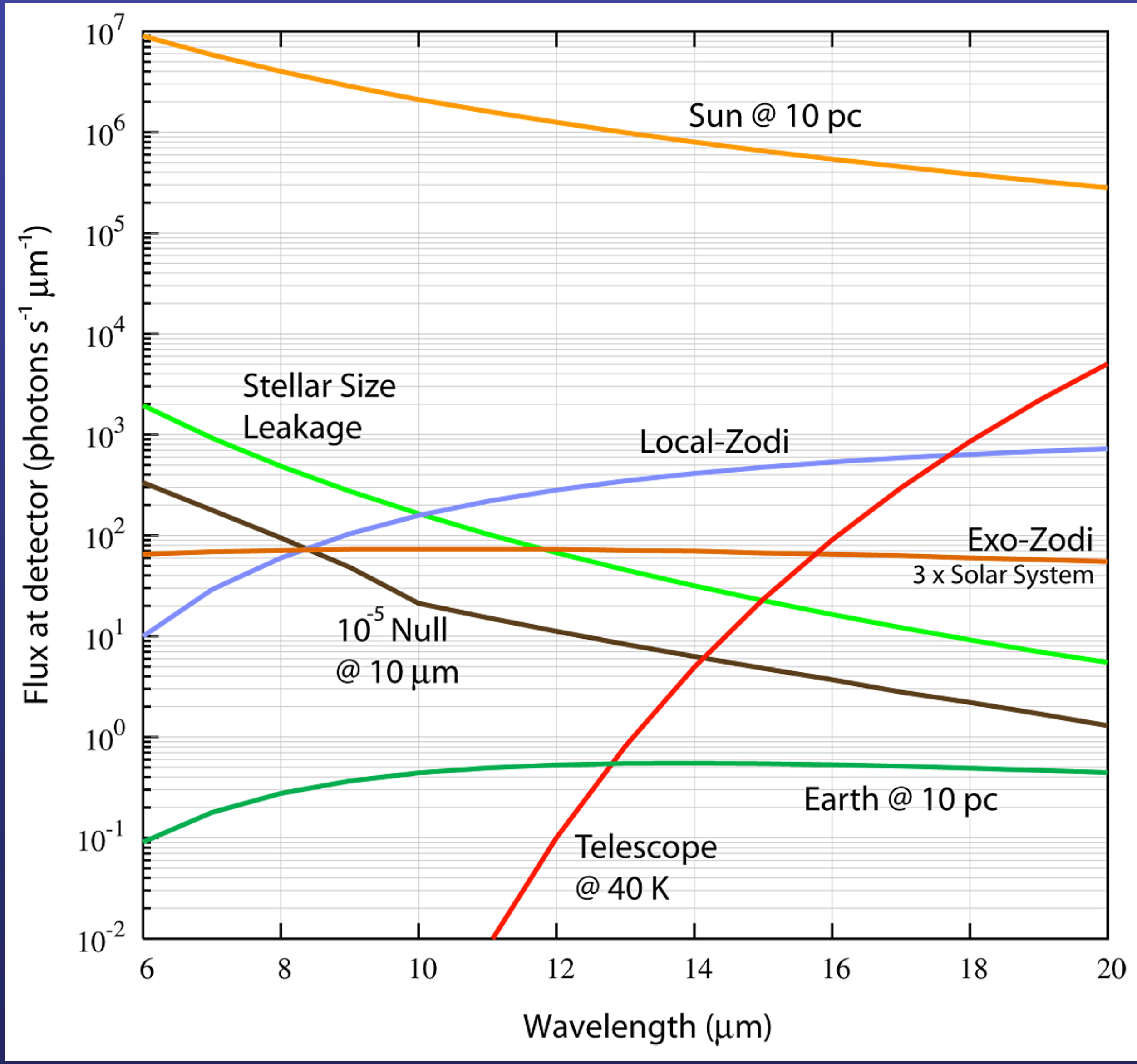
The **Wide-field Imaging Interferometry Testbed (WIIT)** was built to develop a wide field-of-view optical/IR imaging interferometry technique

A detector array is substituted for the single-pixel detector used in a conventional Michelson (pupil plane) beam combiner, and a scanning optical delay line is used to provide spectroscopic information and compensate for external delay

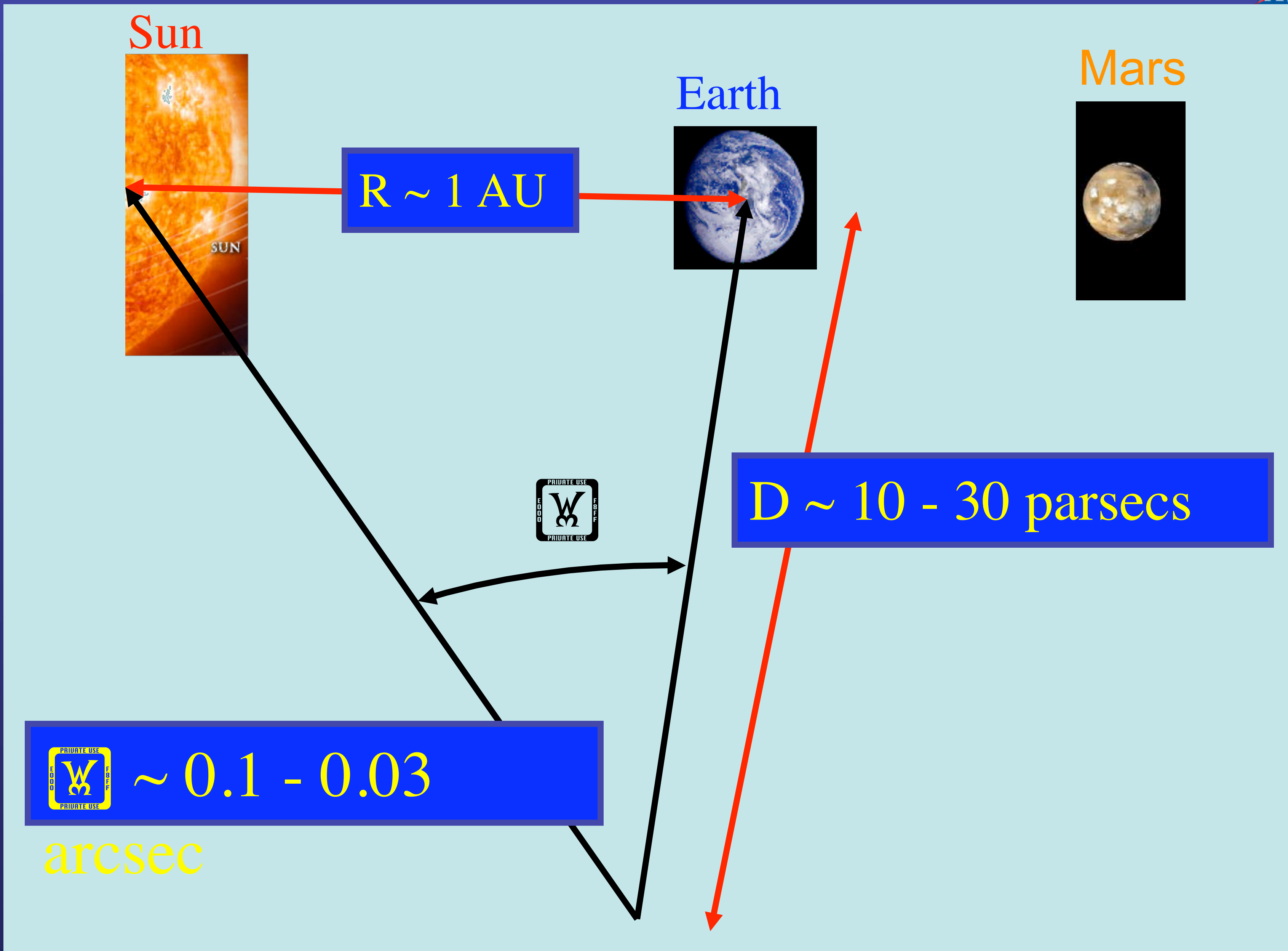




Sources of Noise at Mid-Infrared Wavelengths



Why high angular resolution is needed



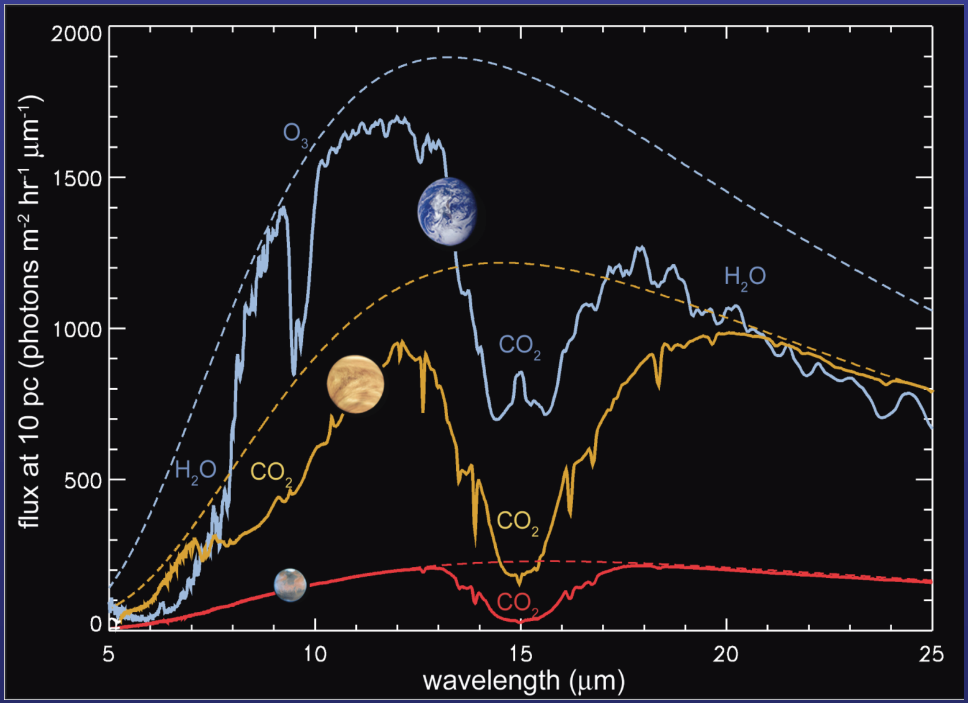
Flagship Mission Requirement Summary

Flagship Interferometer Mission Requirement Summary	
Star Types	F, G, K, selected, nearby M, and others
Habitable Zone	0.7–1.5 (1.8) AU scaled as $L^{1/2}$ *(Note *)*
Number of Stars to Search	>150
Completeness for Each Core Star	90%
Minimum Number of Visits per Target	3
Minimum Planet Size	0.5–1.0 Earth Area
Geometric Albedo	Earth's
Spectral Range and Resolution	6.5–18 [20] μm; R = 25 [50]
Characterization Completeness	Spectra of 50% of Detected or 10 Planets Maximum
Giant Planets	Jupiter Flux, 5 AU, 50% of Stars
Maximum Tolerable Exozodiacal Emission	10 times Solar System Zodiacal Cloud

*There are two definitions in the literature for the outer limit of the habitable zone. The first is 1.5 AU scaled to the luminosity to the ½ power based on Kasting et al. (1993). The second is 1.8 AU scaled in the same way from Forget & Pierrehumbert (1997).

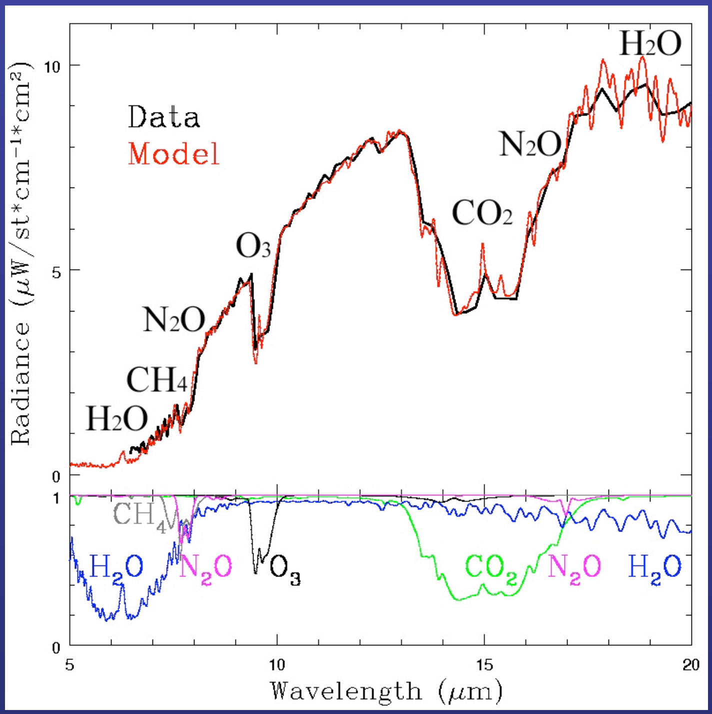
Technology for a Mid-IR Interferometer

- Science Requirements
- Architecture trade studies



- Starlight suppression
  - Null depth & bandwidth
  - Null stability
- Formation flying
  - Formation control
  - Formation sensing
  - Propulsion systems
- Cryogenic systems
  - Active components
  - Cryogenic structures
  - Passive cooling
  - Cryocoolers
- Integrated Modeling
  - Model validation and testbeds

Earth Spectrum

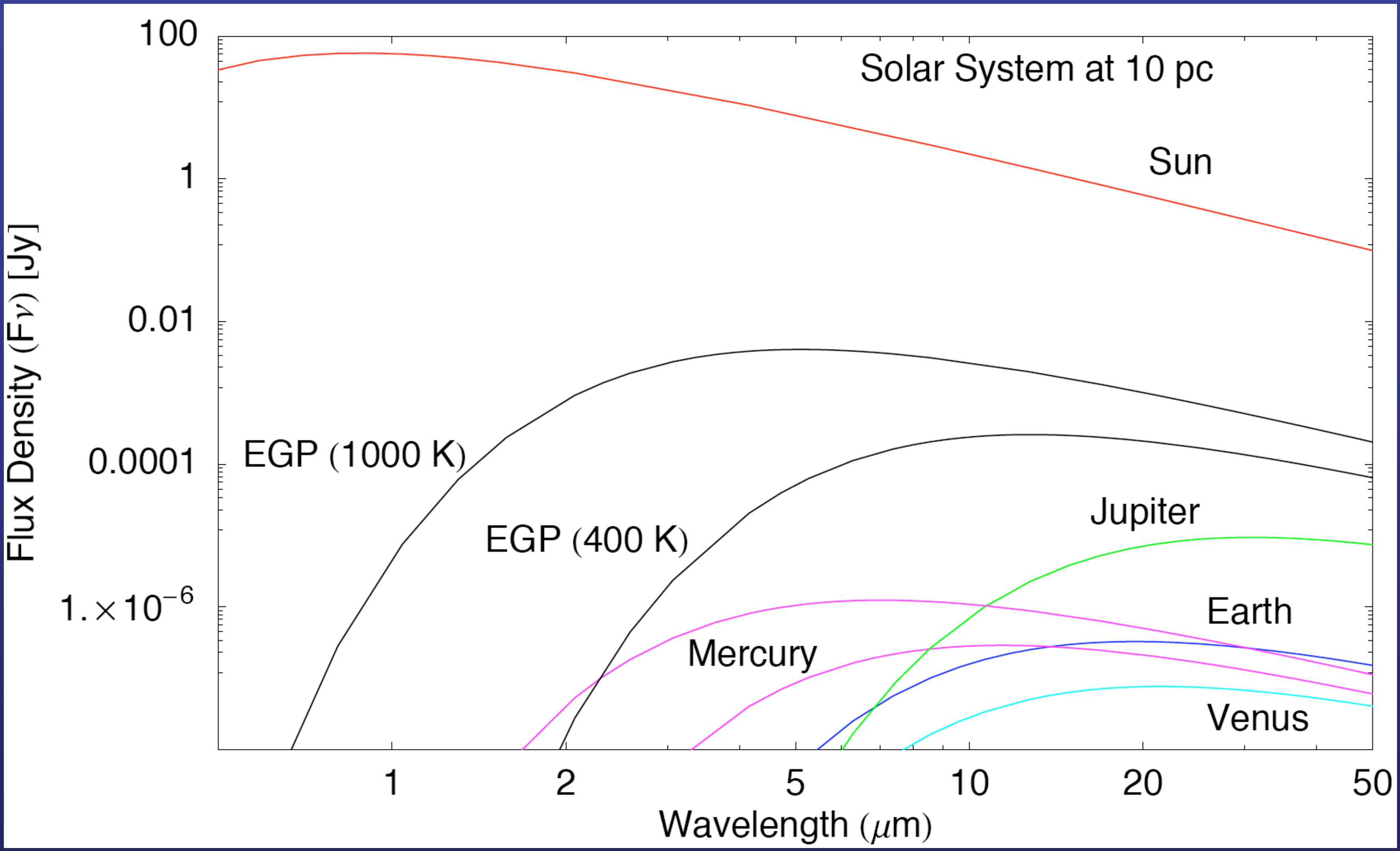


Earth's spectrum shows absorption features from many species, including ozone, nitrous oxide, water vapor, carbon dioxide, and methane

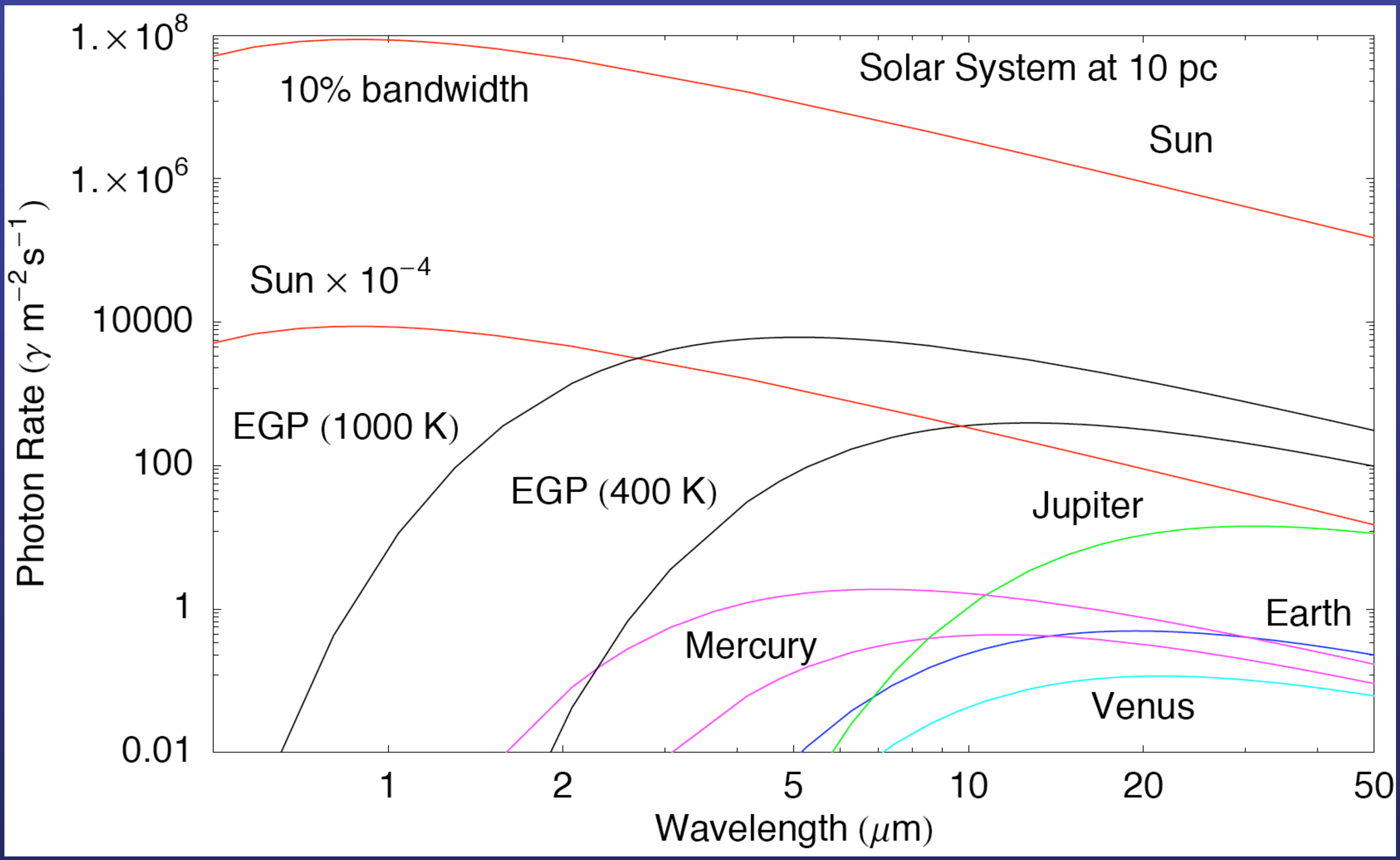
Biosignatures are molecules out of equilibrium such as oxygen, ozone, and methane or nitrous oxide.

Spectroscopy with R~50 is adequate to resolve these features.

Why High Sensitivity is Needed: Photometry of Our Planets and EGPs

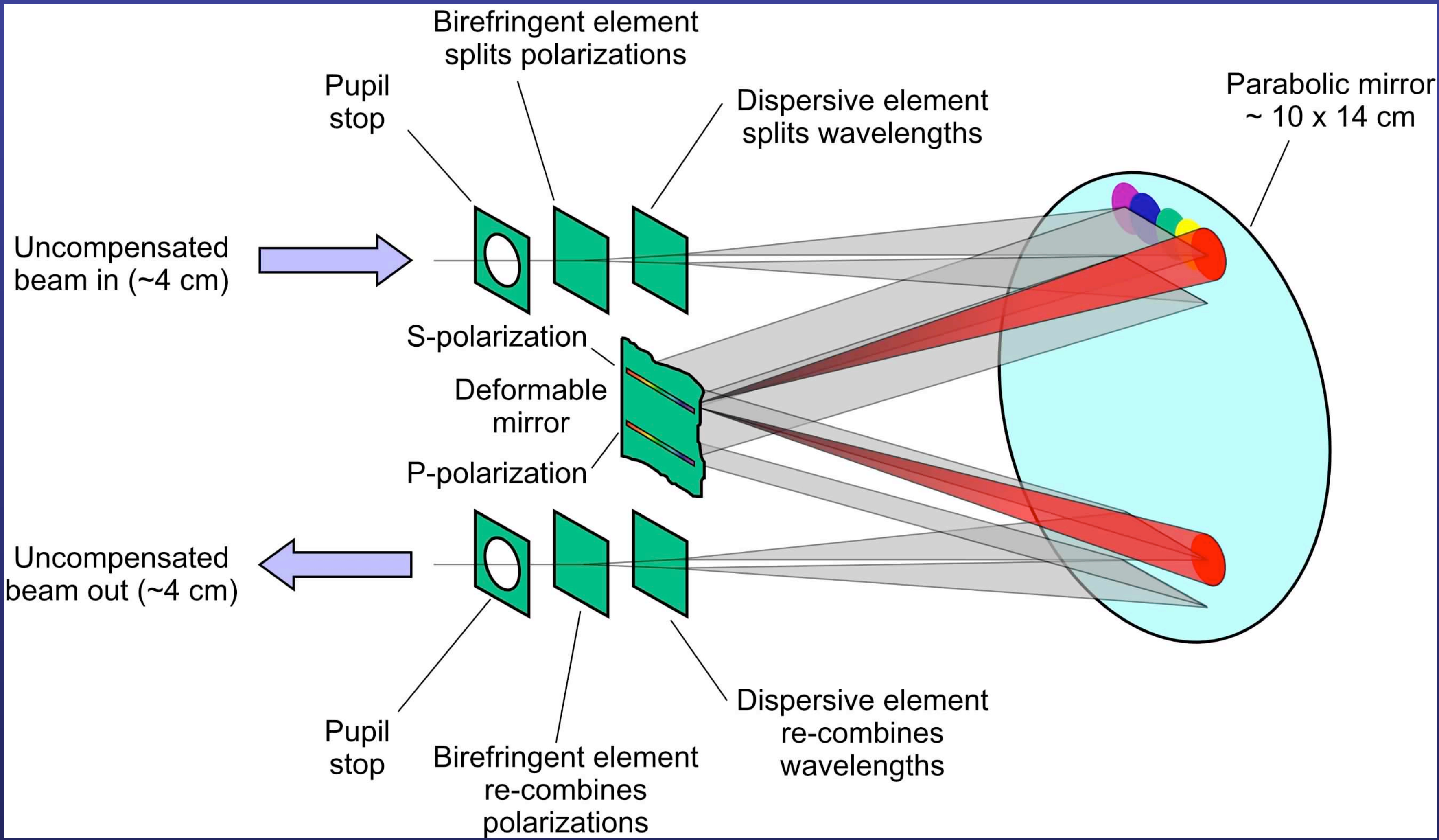


Photon Rates



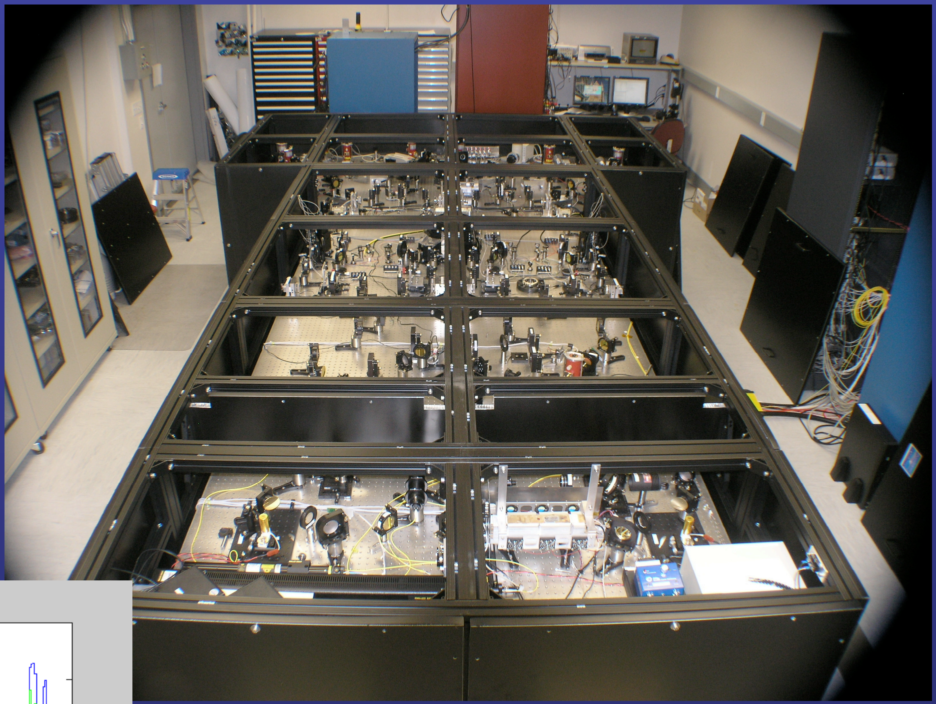
Photon Rates are high enough that only modest apertures are needed!

Broadband Starlight Suppression with a Deformable Mirror



Chopping, Averaging, Array Rotation

- **Planet Detection Testbed** (PDT)
  - Demonstrate array rotation, chopping, and averaging
  - Planet signal extraction with a 4-beam array
  - Planet signal < 10^{-6} relative to the star
  - Residual starlight suppression > 100.



Planet Detection Testbed

Planet signal extraction with the Planet DetectionTestbed: Planet signal 940,000 fainter than the star with null depth of 70,000 to 100,000. (Preparations for Milestone #4)